UNIVERSITY OF THE WITWATERSRAND

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A COMPARATIVE INVESTIGATION ON PERFORMANCE AND WHICH IS THE PREFERRED METHODOLOGY FOR SPECTRUM MANAGEMENT; GEO-LOCATION SPECTRUM DATABASE OR SPECTRUM SENSING.

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A Research Report submitted to the Faculty of Engineering and the Built Environment, University of Witwatersrand, in the partial fulfilment of the requirements for the degree of Master of Science in Engineering Johannesburg, 2015.

DECLARATION

I declare that this research report is my own work. It is being submitted for the Degree of Master of Science to the University of Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination to any other University.

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ABSTRACT

Due to the enormous demand for multimedia services which relies hugely on the availability of spectrum, service providers and technologist are devising a means or method which is able to fully satisfy these growing demands. The availability of spectrum to meet these demands has been a lingering issue for the past couple of years. Many would have it tagged as spectrum scarcity but really the main problem is not how scarce the spectrum is but how efficiently allocated to use is the spectrum. Once such inefficiency is tackled effectively, then we are a step closer in meeting the enormous demands for uninterrupted services. However, to do so, there are techniques or methodologies being developed to aid in the efficient management of spectrum.

In this research project, two methodologies were considered and the efficiency of these methodologies in the areas of spectrum management. The Geo-location Spectrum Database (GLSD) which is the most adopted technique and the Cognitive radio spectrum sensing technique are currently the available techniques in place. The TV whitespaces (TVWS) was explored using both techniques and certain comparison based on performances; implementation, practicability, cost and flexibility were used as an evaluation parameter in arriving at a conclusion.

After accessing both methodologies, conclusions were deduced on the preferred methodology and how its use would efficiently solve the issues encountered in spectrum management.

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DEDICATION

This work is dedicated to my family and to those that find it useful.

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LIST OF ABBREVIATIONS

AWGN – Additive White Gaussian Noise

A/D –Analog to Digital

BER –Bit Error Rate

CR –Cognitive Radio

CTS –Clear To Send

CFD –Cyclo-stationary Feature Detection

CDBS –Consolidated Database System

CeTAS –Centre for Telecommunication Access and Services

DSA –Dynamic Spectrum Access

DSSS –Direct Sequence Spread Spectrum

DUC –Digital up Converters

DDC –Digital down converters

DPC –Dirty Paper Coding

DTT –Digital Terrestrial Television

DVB –Digital Video Broadcasting

ECC –Electronic Communications Committee

EIRP –Effective Isotropic Radiated Power

FFT –Fast Fourier Transform

FCC –Federal Communications Commission

FPGA –Field Programmable Gate Away

FHSS –Frequency-hopping Spread Spectrum

GUI –Graphical User Interface

GPS –Global Positioning System

GSM –Global System for Mobile Communication

GLSD –Geo-location Spectrum Database

GRC –GNU Radio Companion

HAAT –Height above Area Terrain

ICASA –Independent Communications Authority of South Africa

ITU –International Telecommunications Union

ISM –Industrial, Scientific and Medical

OSA –Opportunistic Spectrum Access

Ofcom –Office of Communications UK

MCL –Minimum Coupling Loss

PSD –Power Spectral Density

PUE – Primary User Emulation

PMSE –Programme Making Special Events

PU –Primary User

QoS –Quality of Service

ROC –Receiver Operating Characteristics

RTS –Request to Send

SU –Secondary User

SNR –Signal to Noise Ratio

SDR –Software Define Radio

SCF –Spectral correlation function

TAM –Technology Acceptance Model

TVWS –TV White Space

UMTS –Universal Mobile Telecommunication System

UHF –Ultra High Frequency

UHD –Universal Hardware Device

ULS –Universal Licensing System

USRP –Universal Software Radio Peripheral

VHF –Very High Frequency

WPAR –Weighted Probability of Area Recovered

WSD –White Space Device

1.0 INTRODUCTION

1.1. Introduction

The ability to transport messages at a distance with the speed of light, and at little cost, makes spectrum of radio waves a valuable resource. However, radio waves are known for their ability to interfere with each other if incorrectly deployed and this could counter the benefits they offer. Spectrum sharing however is an interim solution to spectrum scarcity. Ultimately, the cognitive radio techniques of white space radios can in the end be used to share spectrum. Several approaches such as geographic, time-based, spectrum sensing, and geo-location spectrum database are currently being considered.

The digital switchover commencement is known to create spectrum availability in the TV bands. The white spaces that appear in the TV bands will be effectively utilized. The TV white space (TVWSs) that exists in the TV broadcast frequency spectrum are unused bands. In order to avoid interference with incumbents, the available channel transmission characteristics are matched closely to its surrounding environment. The reasons why TV white spaces (TVWSs) are of special interest are firstly, their propagation characteristic are exceptionally good for wireless communications, hence, it accounts for a minimized propagation loss with increased coverage. Secondly, they require cheap infrastructure for their roll-out, making them suitable for countries that are willing to adopt. [1]

The issue of possible interference with primary users has been a major talking point in TV white space communication. The primary user’s protection has to be guaranteed. Hence, there are three possible techniques available. These techniques are spectrum sensing, beacon use and geo-location spectrum database systems (GLSD). For the sake of the research work, the spectrum sensing and geo-location spectrum database are the major part of concern. Spectrum sensing is a wireless communication where a transceiver listens to the frequency band and can intelligently detect communication channels that are available and instantly switch to these available channels without causing interference.

While a geo-location spectrum database is also a wireless communication in which the transceiver consults a spectrum database remotely for available channels and must wait for response from the spectrum database before switching to the available channel.

This technology has been increasingly adopted by most developed countries, the Federal Communication Commission (FCC) of the United States and Electronic Communications Committee (ECC) of the United Kingdom [30, 31, and 32] are major players in the adoption of this methodology. To request for available channels in the TV whitespaces, a White Space Device (WSD) must interact with a geo-location spectrum database indicating its location and request for available channels. Then the geo-location spectrum database responds with a list of available channels and their permitted transmit power for that particular proximity. The White Space Device (WSD) selects one of the available channels and begins transmission.

The aim of this research work is to find from a technological aspect which is the preferred methodology for spectrum management; geo-location spectrum database or spectrum sensing? Hence, some related research and theoretical studies in cognitive radio and TV white space communications would be done first, with more focus on current activities, standardization processes, and related projects. Once the background and present TV white space communications is analysed, a geo-location spectrum database is also analysed to prove the potential of this technology. Then the experimental approach will also be discussed. The spectrum sensing approach is implemented using Software Define Radio (SDR) and Universal Software Radio Peripheral (USRP). The software define radio is an open source signal processing and communication applications development platform which focuses on implementing these signal processing and communication with low cost external radio frequency hardware. It’s primarily used in wireless communications research with the view of implementing software radio systems in real time. The operation of the geo-location spectrum database will also be established through a web interface. Ultimately, a private and accessible geo-location spectrum database system is used. However, certain considerations such as the lack of official regulatory, established standards and actual transmission data i.e. data from TV broadcasters, wireless microphones etc. were noted. The result obtained from the experiment was evaluated based on the performances of both TV white space methodologies.

The performances of both methodologies were categorized as follows:

- Performances in terms of ability to carefully detect spectrum holes or TV white spaces and to exploit these whitespaces without causing inference to incumbents. The geo-location spectrum database methodology was able to detect TV whitespaces at the time of implementation while the spectrum sensing approach failed to detect any possible TV whitespaces at the time of sensing. This does not imply the spectrum sensing approach wasn't efficient enough but it was due to the fact that no available TV whitespaces at the time of sensing. Extensive details on the procedures are described in the research report.

- Another feature of comparison was in terms of cost and practicality; which approach was much easily implemented and how fast, cost-efficient was it rolled out? Studies have shown that spectrum sensing approach is likely to be the most practical approach to implement due to its low implementation cost and its adaptability with traditional systems [49]. Hence, based on the implementation of both methodologies, the spectrum sensing approach (energy detection) was easily implemented because it doesn't need prior knowledge of PUs and it is primarily operated on energy levels or threshold on the frequency band. While the geo-location spectrum database needed a more coordinated activity to setup.
- How efficient is the spectrum being utilized? By efficiency of spectrum use, this implies the ability of the cognitive devices to use as much spectrum as possible in a given location. Both methodologies proved to be spectrum efficient at the time of implementation.
- Flexibility: Subject to the implementation procedures, the geo-location spectrum database approach proved to be a more flexible methodology when compared to the spectrum sensing methodology.

After the analysis the results of both methodologies and looking to other TV white space initiatives, some considerations for future work was considered.

1.2. Motivation

Most countries (African countries with the majority) are set to commence the Digital Migration plan set out by the International Telecommunications Union (ITU), this migration is said to pave way for effective utilization of the under-utilized spectrum which is currently been occupied by the TV broadcasting sector. These proposed an available spectrum band is the key to unlocking uninterrupted broadband access in the major parts of the world.

However, a technology that would effectively and efficiently manage the users on the band with less interference issues is a key enabler to efficient and uninterrupted broadband access.

The Dynamic Spectrum Access (DSA) technology will effectively utilize the TV whitespaces present and provide unlimited Broadband access to end users.

1.3. Objectives

Due to the commencement of the Digital Migration in South Africa, this research work will investigate based on performance, cost, practicality and flexibility which methodology will be more effective and efficient in implementing Dynamic Spectrum Access in TV whitespaces (TVWS) in South Africa.

The main focus of this research work is to safely guide the Independent Communications Authority of South Africa (ICASA) on the preferred Dynamic Spectrum Access technology to deploy and how safe (in terms of interference level) the technology can be used to exploit the TV whitespaces available and efficient use of the spectrum generally.

This research work will provide the guidelines and suggest an efficient approach to implement Dynamic Spectrum Access (DSA) in South Africa with minimized interference issues.

1.4. Scope of the Research Report

This research report is divided into five chapters and a list of references and appendix.

Chapter one gives a brief introduction into the subject matter, it also points out the need to investigate both methodologies, presents the research problem and objectives for this research work. Chapter two is the literature survey. Chapter two begins with related work, spectrum occupancy, introduction to TV whitespace communications, establishing operational principle and architecture of both cognitive radio and geo-location spectrum database technology along with the technical issues and considerations that must be put in place when choosing one technology over the other. This chapter further reviews the evolution of cognitive radio subject to Dynamic Spectrum Access (DSA) and spectrum management. It also discusses the introduction of geo-location spectrum database in the industry as means to curb out challenges faced with cognitive radio deployment i.e. spectrum sensing.

Furthermore, this chapter also compares the key aspects of both technologies and concludes with a view on geo-location spectrum database deployment in South Africa.

Chapter three serves as a basic introduction to the subject of Dynamic Spectrum Access (DSA) technologies for TV whitespaces, and validates the need for this investigation by providing an overview of the key research questions. It also outlines the various enabling sensing techniques and their performance metrics and capabilities. It further discusses the instabilities with the sensing approach, the advantages the geo-location spectrum database has over spectrum sensing and the benefits of building on a spectrum database. It finally concludes with the setbacks of building on a spectrum database.

Chapter four begins with an introduction into the experimental procedures and scenarios the experiments were conducted in. The objectives of the research and methodology used in the experimentation that investigate the problem. Assumptions and baseline testing will be conducted to establish control parameters for subsequent test results. Results are described and summarized with key findings. The conclusion of all testing will be stated as well.

Chapter five provides an overall conclusion to the investigation. This chapter reviews the intent of the research, and ensure all objectives and key research questions have been enormously answered. It concludes the overall research with recommendations and potential future research topic in spectrum management.

1.5. Summary

This chapter briefly introduced the subject matter which is the preferred methodology to spectrum management; Geo-location Spectrum Database (GLSD) or Cognitive Radio spectrum sensing technique. It also outlined the objectives and scope of this research report.

2.0 LITERATURE SURVEY

2.1. Related work

Spectrum occupancy measurement is the ability to detect at a given location the availability of spectrum on a temporal basis. Studies and results are presented to support the relevance of investigating the best means of spectrum utilization in the RF spectrum.

Recently, extensive research work has been carried out on what mechanism to adopt in order to exploit "white spaces" available on TV spectrum after the digital switchover. This extensive research work paved the way for cognitive spectrum sensing access and geo-location spectrum database access (GLSD). Though questions arise as to which mechanism remains effective and could be easily deployed. In the publication, "A survey of cognitive radio access to TV white space" [2], the author discussed extensively the challenges experienced when deploying Dynamic Spectrum Access (DSA) technologies with more reference made on spectrum sensing and possible solutions. In [3], the author briefly discussed the challenges faced with Dynamic Spectrum Access (DSA) technologies with spectrum sensing at the focal point of attention and possible solutions to the challenges experienced. In [4], the author extensively highlighted the advantages and disadvantages associated with spectrum sensing and Geo-location Spectrum Database (GLSD) techniques with more attention towards the spectrum database and how this technique would effectively exploit spatial temporal spectrum hole. However, Fitch *et al. in* [5], argued that in the future, both spectrum database and spectrum sensing techniques will be used together in order to have flexibility and achieve maximum efficiency for secondary users. In [6, 9], it was quoted that "the Federal Communications Commission (FCC) and Electronic Communications Commission (ECC)" have proposed geo-location database usage as a short-term solution for primary system detection and interference avoidance. The question then arises, why is it a short term solution and not a final solution to exploiting the TV white spaces? Federal Communications Commission (FCC) also outlined the reason being that the spectrum database cannot specify the permanent maximum allowed white space device (WSD) transmission power, due to the possible primary system changes as the reason why geo-location is not yet considered a final solution to exploiting TVWS [6, 9].

Also it pointed out how this short term approach eliminates the hidden node problem encountered using sensing. The hidden node problem occurs when there is an obstruction of the primary transmitter signal to the CR user. This obstruction could be as a result of multipath fading or interference of signals. In [7], the authors discussed about various bands such as Radar, TV and Cellular band respectively and which suitable Dynamic Spectrum Access technology is to be deployed in each respective band. The author made more emphasis on the TV band and why the Geo-location Spectrum Database (GLSD) will be suitable for this band.

In [8], the author explained from a technological point of view why geo-location database is increasingly preferred as a solution to the coexistence problems throughout the spectrum. Hence, one feature that makes geo-location database much more desirable is how it solves the problem of clearing a license exempt band for re-allocation to licensed use. In a report from Office of Communication United Kingdom (Ofcom) dated November, 2012 [9], key issues were listed to enhance communication between a white space device (WSD) and geo-location database (GLSD), issues such as information which includes location, location accuracy, and device type etc., is to be provided by the white space device (WSD) to the geo-location database (GLSD). In [9], the roles of geo-location database to white space device such as ability to interpret white space spectrum usage regulations as an input and provide technical mechanisms for enabling whitespace devices to access TVWS spectrum without interfering with incumbents were extensively discussed. In [10], the author extensively discussed on the design of a location aware spectrum database and how this Dynamic Spectrum Access technology can be implemented in South Africa and highlights the difficulties of spectrum sensing. Also the author specifically elaborated on the modelling algorithm and device parameters that would enable the spectrum database to derive lists of frequencies that could be available for white space devices and the rate at which white space devices (WSD) need to re-consult the spectrum database.

From an open spectrum perspective, the reliance on geo-location spectrum database control involves a degree of political risk which might not be tolerated in some countries. Regulators often regard spectrum sensing as too unreliable now, but it is an approach that leads to an autonomous device operation and less risk of government disruption of private communication channel. In [11], the leading-edge on Cognitive Radio (CR) and TV whitespace (TVWS) communications was first analysed and in-depth understanding on the argument was acquired.

The idea acquired was used to successfully demonstrate a geo-location spectrum database system which recognises the main requirements for an enhanced TVWS detection and protection of incumbents. This will hopefully contribute to the research on TVWS communications and hopefully will also be useful for commercialization of TVWS database systems.

Apparently, South Africa is yet to proceed with regards to the Digital Switchover after undergoing trials in some regions in the country a couple of years back. Though the trial was a success and it showed how TVWS could be exploited with the means of a geo-location database approach which also presented challenges [50].

2.2. Local observations

In South Africa, a survey conducted for a period of twelve months highlights that radio frequency spectrum in the 900MHz GSM band, 1.8GHz UMTS band, 2.4GHz ISM band and point-to-point links at 4,5,6, and 7GHz respectively are most heavily utilized [12, 13].

In [14], Masonta et al. spectrum occupancy measurements in the 50MHz – 1GHz band are reported for a rural (Philips town) and urban (Pretoria) area in South Africa and a rural (Macha) location in Zambia. The results show a medium level of occupancy at the urban measurement site (Pretoria) and a low level occupancy at the rural sites (Philips town and Macha). It was also noted that certain frequency bands at the three measurement sites had 0% occupancy over the duration of measurement.

In [15], Lysko et al. measured results on the amount of TV whitespaces available in the Universal High Frequency (UHF) terrestrial TV band at a measurement site in the suburb of Bergvliet, Cape Town, South Africa and it was being compared to the predicted white space results obtained by means of free space loss propagation model.

The authors report states that whitespaces in the UHF band could be between 16 and 100 MHz at the time of measurement, depending on the available method used.

In [16], spectrum occupancy measurements were conducted in Johannesburg, Bloemfontein, Port Elizabeth, Cape Town and Durban for a period of seven continuous days in the 450-470MHz band by the Independent Communications Authority of South Africa (ICASA). The band of interest was subdivided into 1600 measurement channels of 12.5 KHz each with a detection threshold of -106 dB. Table 1.0 shows the percentage of channels in the band that showed 0% occupancy over the period of measurement.

In total, 97.26% of the measured channels displayed no activity of sorts during the measurement period. The 450-470 MHz is assigned for fixed links, low power mobile radio, single frequency mobile and trunked mobile applications in South Africa [17].

In [18], spectrum occupancy measurements carried out in Johannesburg, Pretoria, Bloemfontein, Port Elizabeth, Cape Town and Durban for a period of seven continuous days in the 790-862MHz band by the Independent Communications Authority of South Africa (ICASA). The band of interest was subdivided into 5760 measurement channels of 12.5 KHz each with a detection threshold of -106 dB. Table 2.0 shows the percentage of channels in the band that showed 0% occupancy over the period of measurement.

In total, 99.35% of the measured channels showed no activity during the measurement period. Frequency assignments for this spectrum are for terrestrial broadcasting (790-854MHz) and fixed links (856-861.1 MHz) [18].

Table 2.1: Spectrum occupancy statistics for 450-470MHz [16].

City	Inactive channels (%)
Port Elizabeth	**98.12**
Johannesburg	**97.50**
Bloemfontein	**97.25**
Durban	**96.43**
Cape Town	**97.0**

Table 2.2: Spectrum occupancy statistics for 790-862MHz [18].

City	Inactive channels (%)
Port Elizabeth	**99.74**
Johannesburg	**99.84**
Bloemfontein	**99.97**
Durban	**98.58**
Cape Town	**98.59**
Pretoria	**99.36**

In [19], Mitola warned against challenges that could be encountered when a Dynamic Spectrum Access (DSA) capable device performs spectrum sensing. As explained in [21] and [86], a spectrum occupancy does not necessarily imply a successful exploitation of the spectrum.

Currently, spectrum sensing techniques do not accurately sense systems such as the pulsed radar systems (used for Aeronautical Navigation), deep space communications and GPS signals on most cases [19]. This implies that such inefficiency must be considered when exploiting an idle spectrum. Therefore, it’s safe to suggest that the availability of a spectrum does not necessary imply that the spectrum is exploitable for data communications.

2.3. Opportunistic Spectrum Access (OSA)

The number of wireless networks and users increases at an exponential rate annually. In order to contain such increased growth, opportunistic spectrum access techniques are being developed. These techniques include Cognitive Radio (CR) and Dynamic Spectrum Access (DSA) respectively. The technology with an opportunistic ability to share wireless channels with licensed users is Cognitive Radio (CR).

A Cognitive Radio (CR) network offers high bandwidth to mobile users, by first sensing available spectrum for incumbents (spectrum sense). After sensing, it selects the most suitable and available channel from the sensed results (spectrum decision) and then synchronises access and information with other users (spectrum sharing) before it hands-over in case an incumbent is detected (channel mobility) [20].This concept is shown in Fig 2.1 as follows.

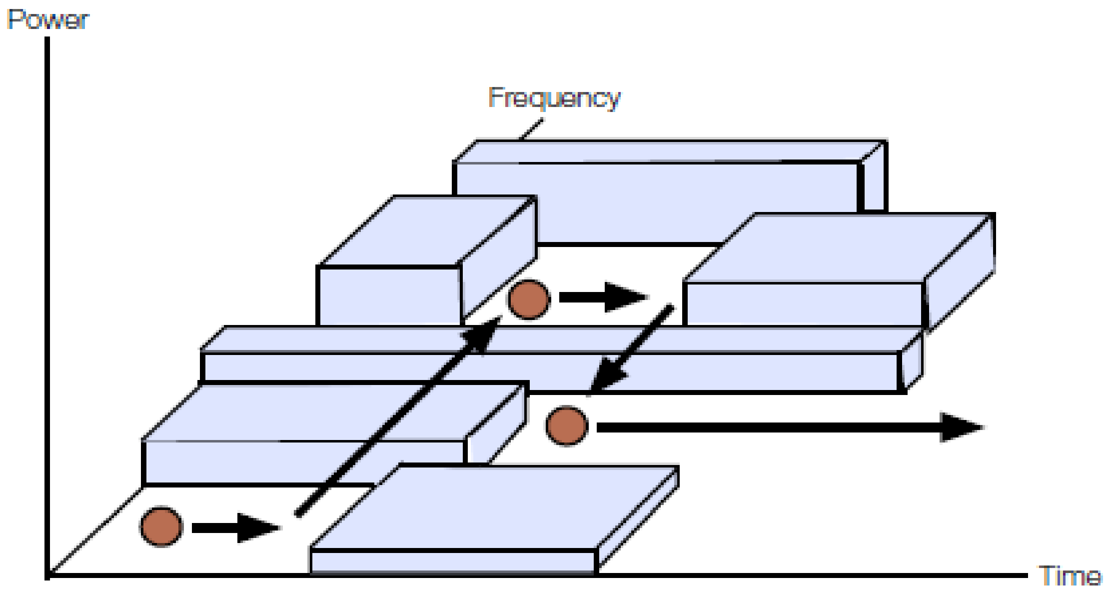

Figure 2.1 Dynamic spectrum access (DSA) concept. [20]

2.4. <u>Remarks</u>

Based on the above local measurement studies carried out in different parts of South Africa, it suggests that, on average, most part of the spectrum is underutilized. Spectrum is underutilized and inefficiently allocated. Apparently, there is currently no viable mechanism in the current regulatory policies that promotes opportunistic use of underutilized spectrum. The above measurements also indicates that the spectrum scarcity is indeed artificial and as a result of the spectrum paradigm on ground.

2.5. COGNITIVE RADIO

A “Cognitive Radio” is defined by the Federal Communications Commission (FCC) as an “*intelligent wireless communication system capable of changing its transceiver parameters based on interaction with the environment in which it operates”* [20]. Due to its knowledge representation, coupled with its automated reasoning, a Cognitive Radio (CR) is currently becoming that gradual evolving technology that would enable dynamic reuse of already licensed or temporally unused spectrum. This feature helps increase spectrum availability for new applications. [20]

2.5.1. Dynamic Spectrum Access (DSA)

Dynamic spectrum access brings about efficiency in spectrum utilization. This term is used to describe a set of technologies and techniques that enable radio communication devices to opportunistically transmit on available radio spectrum. These technologies and techniques ensure that consumers and their devices have wireless bandwidth when needed, thereby introducing flexibility and hence, improving spectrum efficiency. The three major sections of the Dynamic Spectrum Access (DSA) strategies are shown in Figure 2.2 [21].

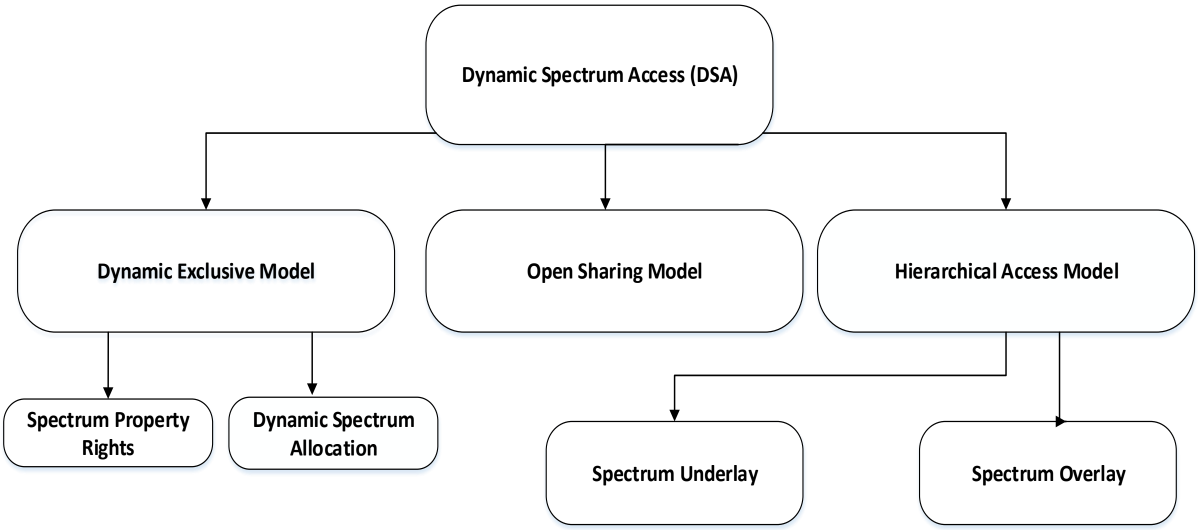

Figure 2.2 Dynamic spectrum access classifications [21]

Dynamic spectrum access sits between the traditional exclusive model of spectrum allocation and the spectrum commons where users share spectrum as commons without prior authorization needed and it often requires that devices operate at low power.

The spectrum commons model have been applied to selected bands, the most successful being the utilization of Industrial Scientific and Medical (ISM) band by Wi-Fi technology.

- **Dynamic exclusive model**

This model illustrates the current static spectrum management policy, with flexibility to the apportioning and use of spectrum while maintaining exclusive access to licensed users. There exist two independent sections under this paradigm, Spectrum property rights [22] and Dynamic spectrum allocation [23]. The latter assigns spectrum dynamically to different services for optimization while the former allows licensed users to sell spectrum.

- **Open sharing model**

The sharing among peers or spectrum commons is done in the open sharing model [24]. The Industrial Scientific and Medical (ISM) band is a good illustration.

- **Hierarchical access model**

This model is known for its categorized access to incumbents and opportunistic users. The secondary users (SU) or the opportunistic users are granted access to occupy the available spectrum while keeping interference with primary users (PU) minimal. There exist two independent groups under this model. The spectrum underlay and spectrum overlay. The former imposes bounds on transmitted power of opportunistic users in order to reduce interference with incumbents. While the latter exploits local and immediate spectrum opportunity by imposing constraints on when and where to transmit [25]. For an efficient output, it is advised that both overlay and underlay models be combined.

2.5.2. Cognitive Radio Technology

This technology allows radio devices to utilize spectrum in entirely sophisticated ways. Cognitive functionality is achieved by the two main features of Cognitive Radio (CR) namely, cognitive potential and re-configurability. Cognitive capability has to do with communication between a radio and its environment in real time so it identifies available licensed spectrum bands called spectrum holes.

In a Cognitive Radio (CR) network, communication is possible through a different medium using various access technologies. This is why the parameters of a Cognitive Radio (CR) can be tuned to suit the background and use the best available frequency band. This feature is called re-configurability [20].

Cognitive radio network architecture

The primary network and cognitive network are the two groups in a Cognitive Radio (CR) network. The primary network is a licensed network with sole rights to access a specific frequency band. Cognitive networks require license to operate in desired band.

The vital features and structure of a Cognitive Radio (CR) network as defined by Akyildiz [20], is illustrated in Figure 2.3 and as follows:

- **Primary User:** The activity of the primary user is being controlled by the base station which includes its licensed operation in certain spectrum bands. This activity should not be disrupted by unauthorized users.

- **Primary Base Station:** Comprises of a static network infrastructural component with spectrum license which often requires licensed and Cognitive Radio (CR) protocols for primary access of Cognitive Radio (CR) users.

- **Cognitive Radio User:** This is a secondary user (SU), spectrum access to this user is allowed by opportunistic means. The Cognitive Radio (CR) user with the ability to sense should be able to link with other Cognitive Radio (CR) users besides the base-station.

- **Cognitive Radio Base-Station:** Comprises of a fixed infrastructure component with cognitive features. It makes possible a connection to a (CR) user without a spectrum access license.

Cognitive Radio (CR) users can link up with the base-station and other CR users. Apparently, three available and possible access types exist in a (CR) network [20]:

- **Cognitive Radio Network Access:** Ability of a CR user to access its own CR base-station. The Cognitive Radio network is the power house of all operations and its intermediate access process does not depend on the primary network.

- **Cognitive Radio Ad Hoc Access:** This is a communication that occurs on both licensed and unlicensed bands between two CR users through ad hoc connections [26, 27].

- **Primary Network Access:** This results when the primary base-station is accessed by the CR user through the licensed band. This is as a result of the communication between the medium access network and the ability of the primary base-station to support CR capabilities.

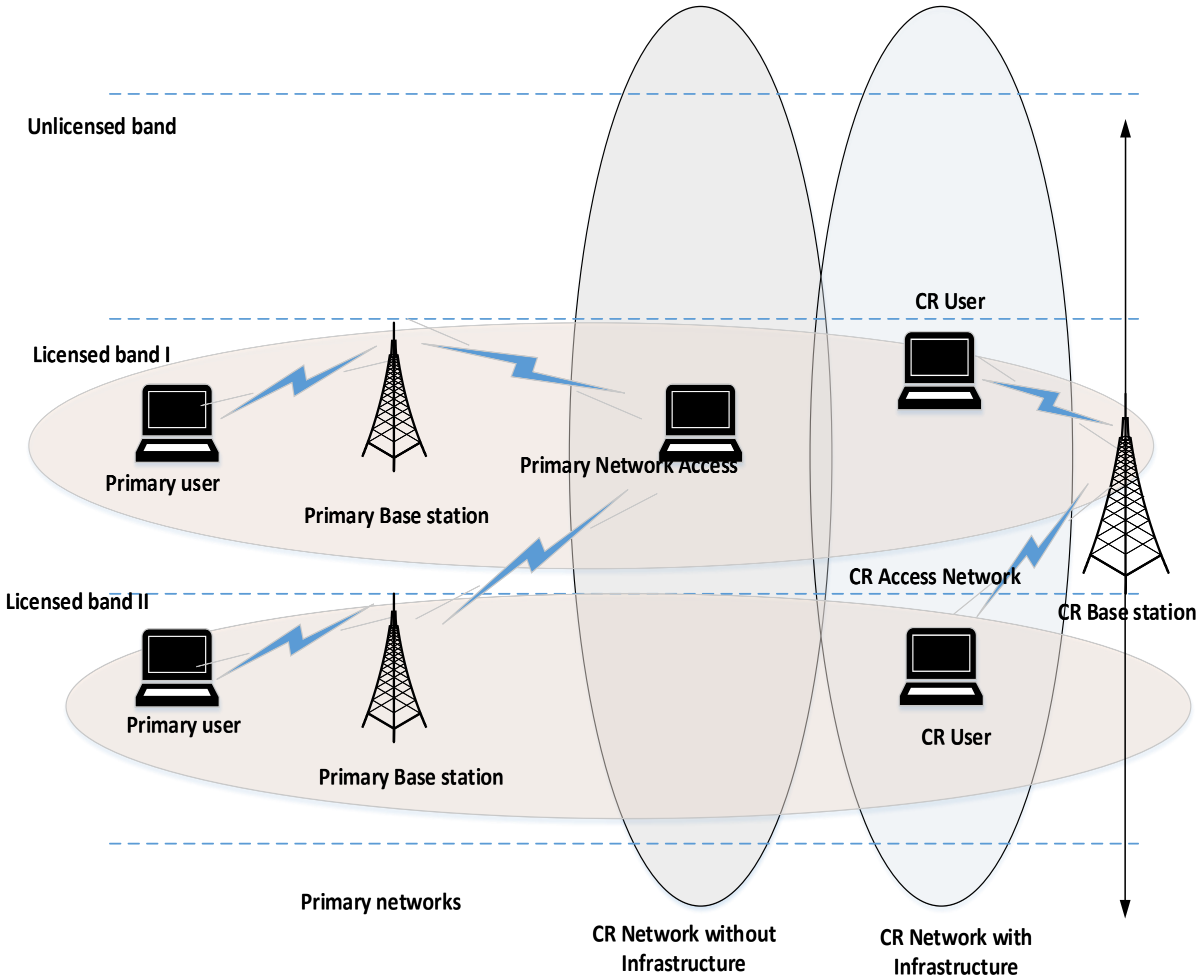

Figure 2.3 Architecture for cognitive radio networks. [1]

Cognitive radio spectrum management

Due to the diverse QoS requirements and CR co-existence with primary networks, certain unique challenges arise and thus, new management functions are required for CR networks with certain critical design challenges. These challenges are interference avoidance, QoS awareness, and seamless communication [20]. To address these challenges, a directory for different functionalities required for spectrum management is provided. The CR spectrum management comprises of various steps which is stated below [1]:

- **Spectrum sensing**

A CR needs to sense spectrum bands either by the primary transmitter detection or the primary receiver detection in order to detect available channels or spectrum holes. Apparently, implementing energy detection technique, CR users experience difficulties in trying to differentiate between incumbent signals and other CR user signals, making spectrum hole detection difficult [1].

Technically, sensing and transmission cannot be executed simultaneously. Ultimately, during sensing, all CR users do not transmit. Furthermore, the inability of the CR users to spot the exact location of the primary user's communication between the primary network and CR network results to poor communication and which is a factor of the poor interference measures in place.

Efficient sensing has always been the key in Cognitive Radio (CR), so it's imperative to discover a most advantageous sensing technique with a minimized sensing period and observation time and is efficient enough with reduced level of interference.

- **Spectrum decision**

A decision paradigm is required for spectrum access. The complexity of this model highly depends on the features considered in the analysis of the spectrum. These features could consist from bit error rate (BER), path loss or the transmit power of the primary user sensed by the secondary user. The CR user should be able to decide on the appropriate and available spectrum band for each precise application. This is feature is known as spectrum decision [1].

- **Spectrum sharing**

A CR user should be able to coordinate its access with other CR users in order to avoid interference issues due to simultaneous access on the same frequency bands. Due to the dynamic nature of spectrum availability, an inter-cell spectrum sharing is essential in a CR network.

The spectrum sharing method makes use of the cell capability by lowering interference caused by opportunistic users while protecting the primary users. Ultimately, various spectrum sharing techniques such as the centralized, cooperative and intra-network exists.

The centralized type of spectrum sharing (spectrum access being synchronized by a foremost user) or distributed (spectrum access coordinated and assigned through some other node), cooperative (proceedings in different nodes are taken into account) or non-cooperative (proceedings in a single-node are observed), intra-network (within the composition of the same CR network) or inter-network (within the composition of different CR networks) [20].

- **Spectrum mobility**

Primary users have preference over secondary users when gaining access to specific frequency bands. In reality, CR users should vacate a frequency band once they sense the presence of licensed users. This process is known as spectrum mobility.

For a secondary user being able to recognise the presence of a primary user on a spectrum band and deciding to vacate the band implies a hand-off / hand-over process occurred and this process is feasible by continuous update of protocols involved.

2.6 WHITE SPACE

A spectrum band is said to be available if it welcomes secondary transmissions with minimal interference upon primary users. The region of space-time-frequency in which secondary access is feasible is described a white space. [28]

A frequency is deemed available at a certain time, but the opportunistic use of this frequency can result in interference to nearby frequency users. Hence, it's imperative to provide adequate access to opportunistic users while protecting primary users from interference. This primarily is the reason a white space is said to be a frequency band in which opportunistic users can transmit without causing interference with incumbents. The Figure 2.4 shows a secondary user "A" initiating a transmission to secondary user "B" but for this to occur, it has to avoid interference with primary transmitters and receivers [21, 28].

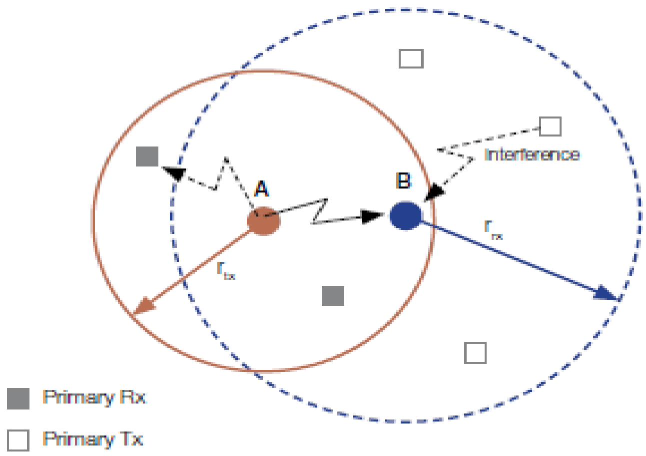

Figure 2.4 White space transmission and interference areas. [28]

These white spaces exist due to the inefficiency experienced with regulatory policies over several years now. However, changing these policies is quite a difficult task because the life of a technology is decided by the way the economy perceives that particular technology. For a technology to achieve a reputable return on investments, that technology should be able to stand the test of time. Dynamic spectrum access techniques are used to exploit the white spaces with minimal interference issues.

2.6.1. TV WHITE SPACE (TVWS)

These are the unused TV channels found within the TV spectrum range i.e. the Very High Frequency (VHF) and Ultra High Frequency (UHF). These are typically known as “buffer” channels. In the past, these buffer channels were implemented as a precautionary step to avoid co-channel interference in the TV bands. It has been for the past couple of years an area of thorough research, this unused portion of the spectrum can be used to provide internet access while avoiding interference with surrounding TV channels. Due to the enormous characteristics of TV broadcast bands in the areas of enabling wide-area internet services and its propagation characteristics, as well as it’s relatively cheap rollout, TV bands have drawn so much attention its way for the past couple of years now.

Migration from analogue TV to digital TV is said to ease up spectrum. However, TV frequency band are known to offer good propagation characteristics and much more. This surging need to free-up spectrum in the TV bands has brought about the occurrence of new technologies that intends to exploit the existing TV white spaces. Currently, developed countries such as the United States and United Kingdom among the least are top in this field.

South Africa currently are still planning the transition from analogue TV to digital TV, so access to a live spectrum database seems to be not exactly easy to accomplish. So for the sake of this investigation, the Council for Scientific Industrial Research (CSIR) spectrum database with focus on South Africa was used. To bring to mind the amount of under-utilized frequency bands, the TV signals are analysed in Figure 2.5 and 2.6 as follows, where the number of available TV white spaces in some particular areas of South Africa is shown [29].

Ultra-High Frequency (UHF) channels in green indicate the channels are available for opportunistic means, while the channels in white apparently indicate these channels are not available for TVWS network operations in that particular area. Due to the restricted access to the geo-location spectrum database, explicit details on the co-channel protected zones and adjacent protected zones could not be analysed further [29].

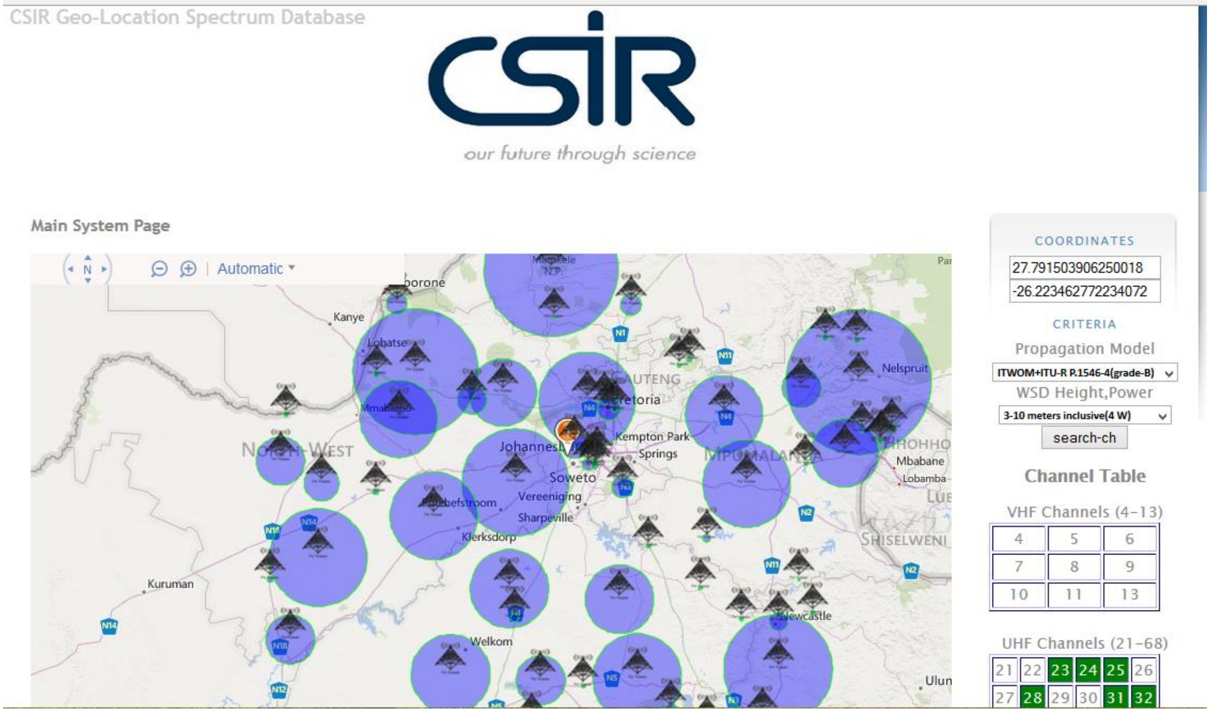

Figure 2.5 TV white space channels in South Africa2015 [29].

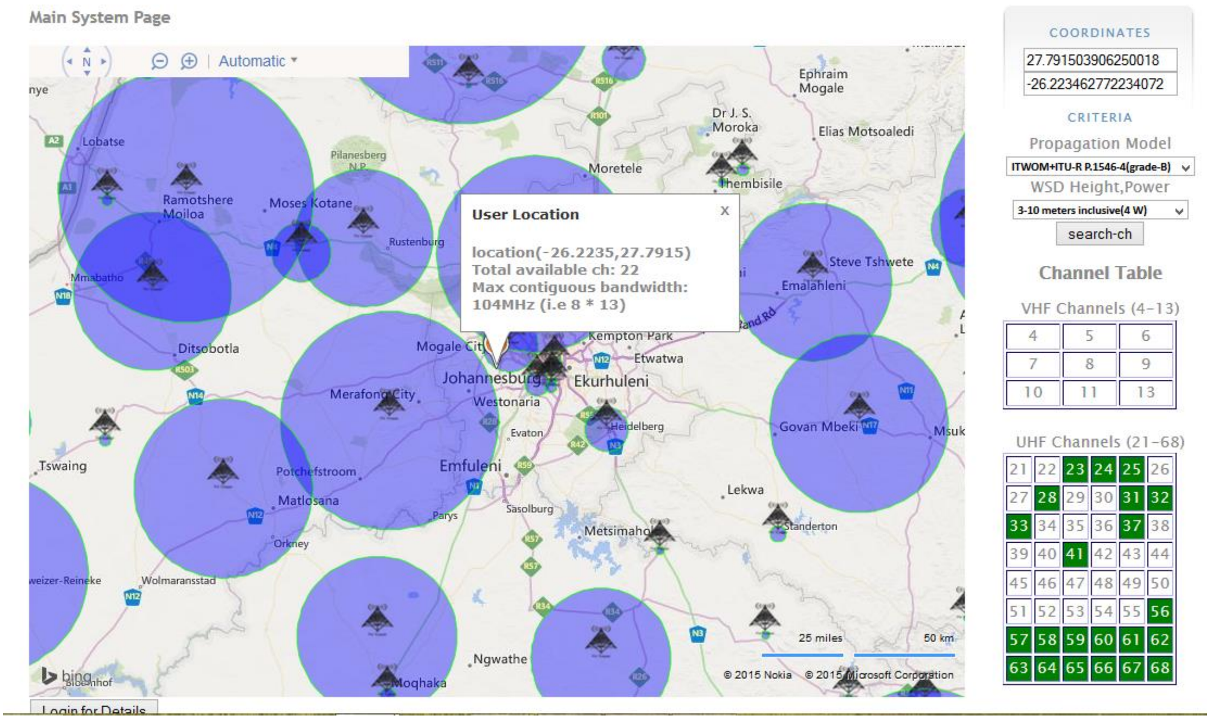

Figure 2.6 shows the available spectrum and their protected zones [29].

2.6.2. SPECTRUM HOLE DETECTION

Considering the properties of a cognitive device, which is to inform the opportunistic user of any possibility or availability that a frequency band could be used in a given space-time value. If this cognitive device wrongly informs the opportunistic user, a spectrum opening is forfeited due to the false alarm and this could invariably lead to collision or interference as the case may be. As shown in Figure 2.7, a lesser false alarm probability "Ɛ" denotes an increased misdetection probability "Ơ" and vice-versa.

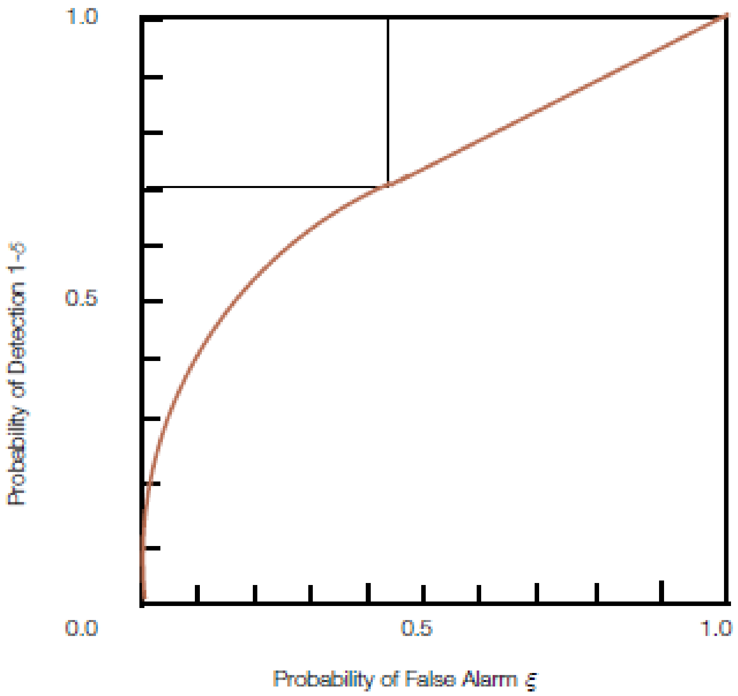

Figure 2.7 Probability of white space detection [28]

In Figure 2.8, a primary transmitter and receiver are shown [28]. With zero interference, at radiusr_{dec}, a receiver within the orange circle can interpret incoming signal received via the transmitter. While a receiver beyond the orange circle cannot interpret incoming signal. Ultimately, to grant opportunistic access, a certain amount of interference is allowed. The grey circle is the safe region within which incumbent receivers are allowed to decode the acquired signal. The "danger zone" is the space between both circles and a primary receiver has no jurisdiction over transmitted signals when a secondary user occupies the space.

A no-talk region (white circle) is setup around the primary receivers for their protection, inside which secondary users are not permitted to transmit.

In Figure 2.8a, the secondary user transmits at a very low power and this affects the no-talk region (makes it small). However, an increase in the transmit power results to an increased no-talk region. i.e. transmit power could invariably be directly proportional to the no-talk region. (Figure 2.8b)

Ultimately, it can be deduced that since the global no-talk area is the summation of the no-talk zones of all the primary receivers, a spectrum hole is the extension of the same [28]. Therefore, for opportunistic users to be able to sense these holes, they have to be aware of the presence of primary receivers. To obtain access to this data, primary involvement is essential and the opportunistic system needs be able to locate primary receivers by sensing them.

Figure 2.8 Primary transmitters protection area and receivers decoding area for low and high transmit powers. [28]

Another problem is when the secondary user fails to decode the primary transmitters signal, assuming the signal to be noise or interference then decides not to communicate within the spectrum hole. However, technique such as the dirty paper coding (DPC) exists to tackle such difficulties. The challenge is, this technique is not robust enough to sort out these problems.

2.6.3. METRICS AND MODELS

An opportunistic user needs to be aware of its presence pertaining to the primary transmitters so as to avoid interference with primary receivers [33]. However, to determine the location of both the primary transmitters and receivers always seem difficult. In order to do so, certain enabling algorithms are implemented to help detect the location of primary transmitters. Such enabling algorithms include the energy detector, matched filter detector and cyclo-stationary detector.

There are several ways to identify white spaces and some other metrics used to evaluate their performances [28]. The metrics used to measure performances are explained briefly below:

Signal-to-noise ratio (SNR)

The Signal-to-Noise Ratio (SNR) is predominantly an approach used by secondary users in estimating the received strength of the primary signal from the incumbent transmitter. The threshold of the relay signal is a factor used by the secondary user in determining its amplitude away from the incumbent transmitter [28]. However, it is necessary to determine the best transmit power in which the secondary user can operate on without causing interference. The question now arises: what level of sensing is required by the secondary user to conclude that the primary system is beyond the no-talk radius? Only then the opportunistic user is permitted to communicate if the acquired power from the primary user is less than $p_t - 10log_{10}(r_n^{\alpha})$ i.e. where P (in dBm) is the acquired primary power at the secondary ratio. If the incumbent user relay threshold is denoted $\boldsymbol{p_t}$, the attenuation factor α, the global no talk zone (r_n) and the measured primary power at the secondary user is P, the opportunistic user transmit threshold is defined as [28]:

$$\boldsymbol{P \underset{use}{\overset{do\ not\ use}{\gtrless}} p_t - 10log_{10}(r_n^{\alpha})} \quad \textbf{(2.1)}$$

The above equation concludes the possibility of a system to perfectly determine its relative position and regain all area away from the no-talk radius given only the received signal strength. This condition implies that the secondary user position could be known by just measuring the received signal strength.

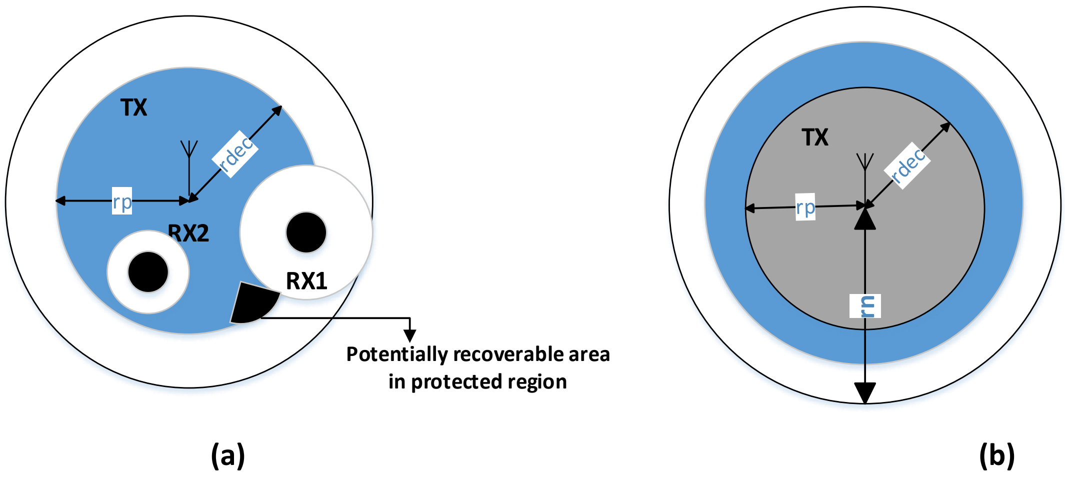

Fig 2.9 (a) the section within the covered region can be recovered if the spots of the primary receivers can be resolved. (b) Global no-talk zone can be defined provided the primary receivers are within the protected region. [28].

The setbacks experienced such as multipath and shadowing effects which invariably reduces its received power, makes the secondary user to assume that the primary user is outside the no-talk region when it's actually within. To evade the shadowing and multipath effects, a budget parameter is made known as stated in the following form [28].

$$\boldsymbol{P} \underset{\boldsymbol{use}}{\overset{\boldsymbol{do\ not\ use}}{\gtrless}} \boldsymbol{p_t - (10log_{10}(r_n^{\alpha}) + \Delta)} \qquad \textbf{(2.2)}$$

Δis the safety factor and its importance is evaluated by the preferred operating point of the system. The value of Δ determines the secondary user's decision to avoid interference with the primary user as well as to regain area for its operation [28]. If it's little, this reduces but doesn't completely eliminate the multipath and shadowing effects. In other words, the secondary user is bound to cause slight interference but more spectrum holes will be detected. If Δ is big, invariably implies zero interference, however, some spectrum holes will be lost.

Traditional sensing metrics

Receiver operating characteristics (ROC): A sensing algorithm can be pictured as a structure that comprises of programs, outputs and control knobs. The program invariably denotes the acquired signal, while the output is the choice to use the band or not. The control knobs are more like design limits such as threshold, sensing time etc. [28].

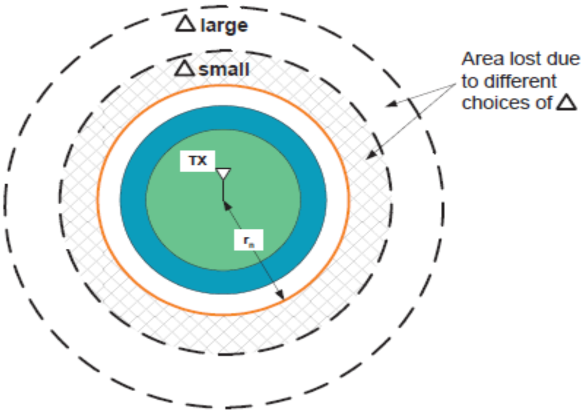

Figure 2.10. The secondary user doesn't lose much once the budget for multipath and shadowing is little (Δ small). [28]

The behaviour of such system is dependent on the Receiver Operating Characteristics (ROC) curve.

Sensitivity: The least value of the operating SNR for which the detector meets a given target P_{MD} and P_{FA} [1].

Sample complexity: The burden for a detector determined by the sensing time necessary to meet a target probability of false alarm (P_{FA}), probability of missed detection (P_{MD}) at a given SNR. The sample complexity and sensitivity are closely interlinked; a slight increase in the sample complexity incurs a larger sensing overhead and overall improves the sensitivity of the detector.

Robustness to uncertainties: This is an essential and functional characteristics for detectors performing at low SNRs. Uncertainties are broadly categorized into device-level uncertainties (like uncertainty in the noise power) and system-level uncertainties (like uncertainty in the shadowing distribution) [28]. By changing legacy metrics such as sensitivity or the SNR wall, this certainly reduces the device-level uncertainties. To be able to comprehend with the system-level insecurity, like the concerns in shadowing, most conditions needs to be incorporated into the specifications of various systems [1]. For example, the 802.22, requires -116 dBm sensitivity (a safety margin of 20dB) [1]. This implies much available white space will be lost.

New system-level metrics

Safety: This metric computes the chances of interference. The probability of potential interference P_{Fr} is the likelihood that the opportunistic user is not over the no-talk region and declares the band as "unused". F_r is the likelihood distribution of the merged multipath and shadowing-induced fading at a distance r from the primary transmitter [1]. This opportunity is dependent on the supposed model of shadowing and multipath. Thus, the Fear of Harmful Interference (F_{HI}) is defined as [1]:

$$\boldsymbol{F_{HI}} = \sup_{0 \leq r \leq r_n} \sup_{Fr \, \epsilon \, \mathbb{F}r} \mathrm{P}_{Fr} \, (\mathbf{D = 0} | r_{actual} = \mathbf{r}) \qquad \textbf{(2.3)}$$

where the outer supremum depicts concerns in the secondary user deployments and the inner supremum depicts the concerns in the fading distribution. [28]

Performance: This is the tendency of an opportunistic user to find white spaces. If a single primary transmitter exists, every spot at a radial sweep where r >r_n would appear to be a white space. There is also a likelihood linked with spotting such an opportunity; this is called the probability of finding the holeP_{FH} [28].

$$\boldsymbol{P_{FH}} \, (\mathbf{r}) = \mathrm{P}_{Fr} \, (\mathbf{D = 0} | r_{actual} = \mathbf{r}), \; \mathbf{r} > r_n \qquad \textbf{(2.4)}$$

However, opportunistic users might be doubtful about the shadowing and fading distributions. In such cases, these opportunistic users do estimate performance using the least case scenario in their uncertainty set. The uncertainty set is apparently much smaller when compared to the uncertainty set used in equation (2.2) to estimate the safety performance to the incumbent user [28]. This invariably means that the incumbent user would not rely or rather will not be able to trust the decision of the secondary user deployment model and hence it decides a larger uncertainty set [28]. However, this does not imply a falsehood in the deployment model of the secondary user, rather it's a safety precautionary measure taken by the primary user. The opportunistic users are familiar with their deployment model well enough as there is no need for them to deceive themselves.

For clarity, the uncertainty set is narrowed down to a single point relying on the total information of the joint shadowing and fading distribution (F_r). The point is to merge the probabilities P_{FH} (r) into one performance metric that permits comparism among various sensing algorithm. This metric is called Weighted Probability of Area Recovered (WPAR) [28].

WPAR:

$$\textbf{WPAR} = \int_{r_n}^{\infty} \boldsymbol{P_{FH}\, w(r) r\, dr = 1} \qquad \textbf{(2.5)}$$

where w(r) is a weighing function that satisfies $\int_{r_n}^{\infty} w(r) r\, dr = 1$ [28]

Models for fading uncertainty

The received primary signal strength P (dBm) can be expressed as [28]:

$$\mathbf{P} = \boldsymbol{p_t} - \mathbf{(l(r) + S + M)} \qquad \textbf{(2.6)}$$

Where p_t is the power of the acquired signal, l (r) is the loss in power due to attenuation at a distance *r* from the transmitted signal, *S* is the loss due to shadowing and *M* is the multipath fading loss. It's practically viable to be able to differentiate the nominal and quantile models for *M* and *S* [28].

The increase in the no-talk zone is as a result of the uncertainty in the primary user's location. A request-to-send (RTS) message to the receiver from the secondary transmitter indicates a spectrum hole has been detected using its established metrics. Then, this is followed by an acknowledge message with a clear-to-send (CTS) from the receiver indicating that the channel has been checked and free for usage [28].

2.6.4. COGNITIVE RADIO LIMITS AND TRADEOFFS

CR being a new technology has certain vital limits that are still yet to be resolved. Many challenges still exist and some design trade-offs still needs restructuring in order to meet the desired wants of the end users.

GEOGRAPHICAL AND DETECTION TRADEOFFS

The previous section elaborated in details the trade-offs experienced, such as the shadowing and multipath effect and how this effect increases the no-talk zone when the secondary user is trying to locate the primary user and the geographical difficulties locating the primary user.

At low Signal-to-noise ratio (SNR), it's hard to detect zero-mean signals and this limits the performance of the detector. To enhance the efficiency of the detector, a pilot signal can be transmitted while a suboptimal detector is introduced to reduce the number of detected samples [34, 35].

NOISE UNCERTAINTY AND QUANTIZATION

If at all possible, the variance is known and the receiver's noise is Gaussian. However, in reality, the reverse is the case i.e. the variance is unknown and the noise is almost Gaussian. This denotes that at very low SNR, the detector fails to detect the signal. [35]

$$SNR_{wall} \ - 10log_{10}[10^{(x/10)} - 1] \qquad (2.7)$$

The introduction of a pilot signal fixes the issue of the noise. This is because of the less likelihood that the noise senses a definite pilot signal.

However, most receivers with built-in Analog to Digital (A/D) converter generates additional received noise which forces an SNR loss in non-coherent detectors. [35]

SINGLE RADIO DETECTOR: LIMITS ON ROBUST SENSING

To meet the constraints of non-interference with the primary receivers, the opportunistic user should be able to acknowledge the presence or absence of an incumbent signal. The CR must be able to sense the incumbent signal in the "band of interest". Although several strategies on how to go about it exist – energy detection, coherent detection just to mention but a few.

The use of coherent detectors eliminates the noise uncertainty in the non-coherent detectors. The shadowing and fading effects limits the efficiency of the coherent detector [34, 35]. Furthermore, the clock-instability and complexity imposes more limits on the coherent processing time and this hinders optimal performance. To achieve optimal performance, cooperation is implemented. However, without cooperation, the sensitivity of the detection algorithm in a secondary system would increase by an amount equal to that of the deepest shadow/fade under which it must detect the incumbent signal. This practically implies that while an un-shadowed system needs to detect a 0dB signal to avoid interference, it would need to detect a -45dB signal to account for the possibility of a 45dB shadow fade. Cooperative sensing tries to take advantage of the dissimilarity of different radios. The fact that a single radio could be faded or shadowed at a particular time doesn't imply all the radios are faded at that same time [34, 35].

Cooperative sensing can salvage more spectrum bands, thereby making available more channels for reuse. This enhancement is directly proportional to the amount of users under cooperation M. Hence, an increase in one results in an increase in the other [35]. Although chances are that there'll be a reduced form of fading while shadowing might happen simultaneously amongst users (rain etc.).

Another method of avoiding single detection problems is to deploy a geo-location spectrum database (GLSD) where the database easily locates primary users and also calculate white space availability [35].

2.7 GEO-LOCATION SPECTRUM DATABASE

A Dynamic Spectrum Access (DSA) enabling technology or algorithm calculates the proximity of a TV coverage area by utilizing the TV signal level emitted from within the coverage area or a particular coverage area. In the case of fading, the signal level being sensed and the distance covered in order to do that are loosely related. Primary users can be guaranteed protection if a very concise algorithm with prioritized decision levels is implemented. However, in most scenarios, the detection level overestimates the precise distance to the primary receivers [36].

A precise enabling algorithm which identifies location of users and estimates the path loss between users (primary and secondary) is the Geo-location Spectrum Database (GLSD). The location identity and path loss ability is possible due to the spectrum database's global awareness of transmitter's location and coverage areas [36]. This awareness enables the spectrum database to efficiently make a spatial spectrum allocation [36]. A Geo-location spectrum database (GLSD) is a wireless communication technique in which the transceiver consults a spectrum database remotely for available channels or frequencies from a particular location and at a certain time and must wait for response from the database before switching over to the available channel. This methodology is an alternative to spectrum sensing technique in CR [37, 38].

The geo-location database in return requests the primary user to provide some parameters and information such as its frequency of operation, transmitted power; size and type of transmit antennas etc. [39]. The concerns of location uncertainties, fading effects and detection errors experienced in the sensing techniques are tackled effectively by the geo-location spectrum database (GLSD) but some trade-offs still exists within the geo-location spectrum database technique such as synchronization and regular update of the database appropriately.

Thanks to the Geo-location Spectrum Database (GLSD) system and the Federal Communication Commission (FCC) in the United States, a flexible approach to opportunistic access of the spectrum is viable. While in Europe, the use of both techniques (sensing and database) has been proposed. Hence, more analysis on the operation of a database system is discussed in details and the different regulatory commissions.

2.7.1. Advances in Dynamic Spectrum Access technologies.

Office of Communication United Kingdom (OFCOM)

Office of Communication (Ofcom) published a consultation on the *"implementation of geo-location spectrum databases in order to optimize the efficiency and flexibility of new wireless technologies"* in November 2009 [30, 31].

A geo-location spectrum database communicates via a base-station then to a WSD on the availability of channels for reuse. This communication follows a particular procedure where Office of Communication (Ofcom) provides a "master device" with a table of various geo-location spectrum database to choose from, then the opportunistic user or device selects its preferred spectrum databases and communicates by sending its location and communication parameters with the help of a Global Positioning System (GPS). The selected spectrum database on receiving the communication parameters accesses it and in return provides the WSD with a table of available channels and their characteristics. The geo-location spectrum database (GLSD) makes use of the algorithms specified by Ofcom to calculate available channels.

Once the synchronization between the master white space devices (WSD) and the geo-location spectrum database is done with, the master WSD then provides available white space tables to the recommended slave devices. In this case, the master device might be a wireless router while the slave device could be your laptops, mobile phones etc.

In the "Digital dividend cognitive access statement on license-exempting cognitive white space devices (WSD) using interleaved spectrum" published in July 2009 [32], Ofcom stated the three possible mechanisms in exploiting white spaces in the TV band. They are sensing, geo-location spectrum database and beacon transmission. Due to high cost infrastructural setup and spectrum inefficiency in its unexpected propagation, the beacon transmission was not considered as a means to utilize white spaces by Ofcom. When also compared to sensing technique, that requires no infrastructure and geo-location spectrum database that considerably incurs less cost and resolves the difficulties encountered in sensing, Ofcom decided to enable both geo-location spectrum database and spectrum sensing.

The listed key issues to be noted when establishing a geo-location spectrum database system are outlined below [31]:

- The data to be made available by the device to the database(s): the information such as device location, device type and preferences etc.
- The data exchanged from the database(s) to the device: available frequencies, maximum transmission power for each geographical location and possibility of connecting to a close or regional database nearby.
- The regularity of update of the database(s) and hence the sequence with which devices will need to re-check: devices should re-consult the database every two hours or less, depending on the mobility.
- The modelling, enabling algorithms and device features to be used to fill the database(s): some recommendations depending on the transmission model, sensitivity and methodology exist.
- The up keep of the database(s): who is to take full responsibility of the database in terms of maintenance and prompt updates!?

Ofcom proposed Operation of a Spectrum Database

The licensing information of Digital Terrestrial Television (DTT) coverage plans must be part of the geo-location database as this would enable other parameter easy synchronization and easy exchange of information. The geo-location database providers will also be updated on any modification on the Digital Terrestrial Television (DTT) coverage parameters. Hence, a link between the geo-location database providers and Programme Making Special Events (PMSE) licensing data is enabled for easy real-time exchange of information between the geo-location database providers and Programme Making Special Events (PMSE) [31].

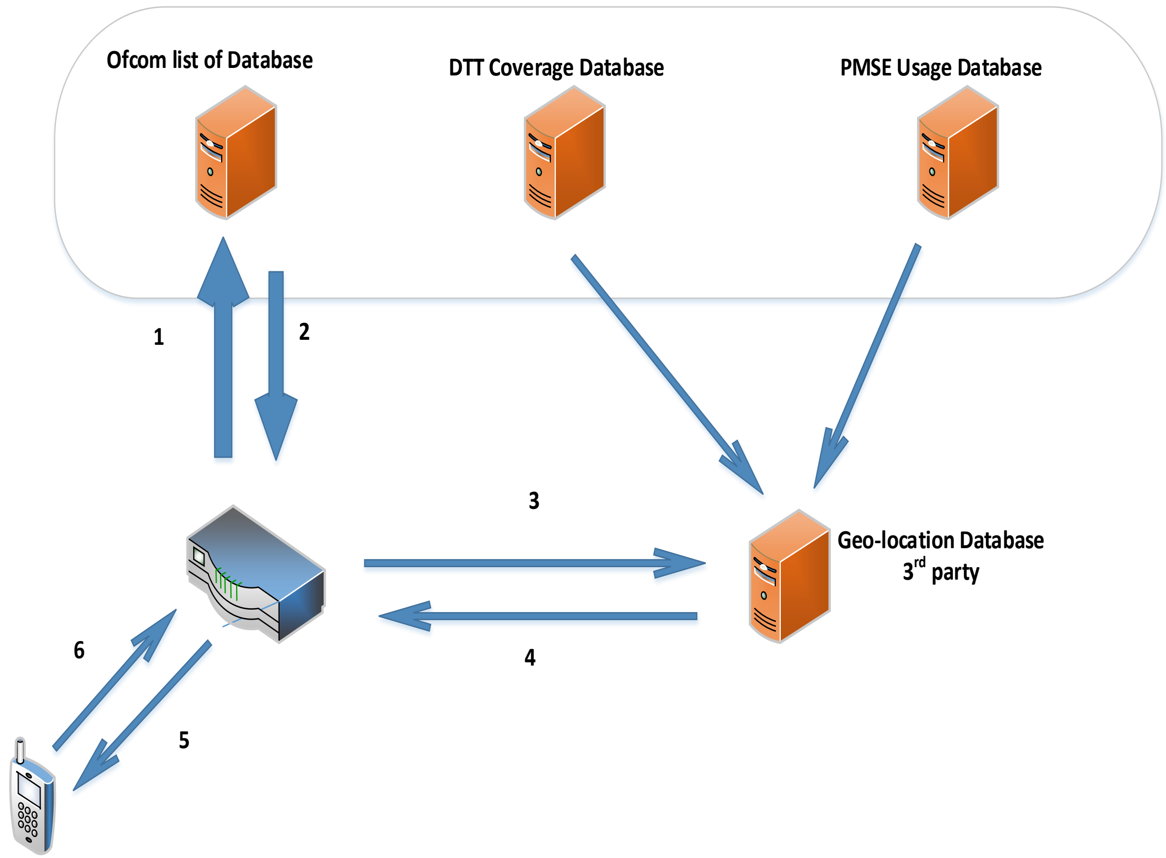

Figure 2.11 Ofcom geo-location database operation architecture [31].

The geo-location database system works as follows [31]:

- The master device connects to the Ofcom website.
- The Ofcom website provides the master device a listing of registered geo-location database valid for 24hours.
- The master device chooses a reliable geo-location database from the table provided and synchronizes with the database by registering with the database and providing some necessary parameters such as accurate device location (in terms of latitude-longitude) to a certainty of 95%, model type and height above ground level.
- Then the geo-location database responds with available frequency bands with various parameters: start and stop frequencies for the channel, maximum power level, channel validity time, if additional sensing is required (if so, then the sensing level in dBm and type of primary usage).
- The master device responds to the slave by providing available frequency information.

- The slave device(s) acknowledges with a data confirmation.

Due to the unknown distance between the master device(s) and slave device(s), this uncertainty could mean that the primary users could be closer to the slave devices and vice-versa and could result to inference. In order to avoid such, the location uncertainty of the WSD is increased. However, this solution could be more complex [31].

Procedures for licensed exempt band

Ofcom concluded that it was more suitable for WSDs to be exempt of license [31]. This would facilitate the order to obtain the framework information of their activity. i.e. the WSDs. In order to do that, the Statutory Instrument (SI) should be consulted.

The master device must stick to certain guidelines in order to be exempt of license [31]:

- Its position accuracy must be of 95% accurate. This accuracy includes the maximum area within which a slave device could be found.
- Query a list of geo-location database provided by Ofcom and select one (this query is done every 24hrs to check validity).
- Strictly adhere to the provided parameters, stop transmission when the validity time expires or when the user moves out from the valid area.
- Spectrum availability to be evenly distributed amongst competitive users.
- Provide the out of band performance indicating the emitted power to the adjacent channels.
- Slave devices are to be managed appropriately by sending the required parameters when requested.
- When the master device stops transmitting, the slave devices are to be put on check or controlled. i.e. transmission stopped also.

US FEDERAL COMMUNICATIONS COMMISSION (FCC)

In September 23rd 2010, the acceptance to use the TV White Spaces (TVWS) for "Super Wi-Fi" technologies was introduced by the FCC since its first significant spectrum modification for unlicensed use in 20 years [39].

Based on the Second Memorandum Opinion and Order (Second MO&O) [40], the wireless microphone users must acknowledge that channels between 7 MHz and 51 MHz will be in use before requesting registration in TV bands while additional sensing technologies to the geo-location database system are not required anymore.

Precautionary steps taken by the FCC to ensure the protection of primary users [39, 40]:

- Two free Ultra High Frequency (UHF) channels were set apart for wireless microphones and other opportunistic users located around the country.
- A certain distance between the secondary users and TV White Space Devices (WSD) were maintained.
- The FCC stated, geo-location database providers are permitted to charge fees for registration of fixed devices.
- These fixed devices must register their location with the geo-location database.
- All devices must contain adaptable power control so as to be able to transmit within the minimum power level available.
- All operational devices must be endorsed by the FCC laboratory, this limits interference.
- The FCC laboratory has the authority to eradicate any harmful equipment from the market.

It's mandatory for a TV spectrum database to contain these two information provided below:

- Licensed services operating in the TV bands.
- Location of registered wireless unlicensed microphones that work regularly.

These stated requirements from the US Federal Communications Commission (FCC) are the least market entry requirements for operators who are willing to adopt the Geo-location Spectrum Database (GLSD) methodology.

Independent Communications Authority of South Africa (ICASA)

The digital migration which supposedly is said to make available Analog TV broadcast spectrum (470-854MHz) for other domestic use is yet to commence. Going by the previous ITU World Radio Conference in 2012 (WRC-12), 694-790MHz frequency band in Region I was allocated for mobile service operations. Hence, 790-862MHz will be available for use and this availability is only for countries in the ITU Region I category. South Africa currently is in the ITU Region I.

On February 18th 2013, ICASA released a position paper on digital migration regulations [41]. The position paper signifies South Africa's willingness to adhere to the International Telecommunications Union (ITU) mandate which was migration from Analog to Digital (A/D) broadcast. This migration from Analog to Digital (A/D) broadcast paved way for trials on the preferred Dynamic Spectrum Access technology to deploy when the migration is complete. There are currently two Dynamic Spectrum Access (DSA) technologies that are gradually being adopted globally, and these technologies are the spectrum sensing and Geo-location spectrum database (GLSD). However, the procurement of the cognitive devices capable of sensing the available radio frequencies and be able to adapt it transmission characteristics in order to avoid interference to incumbents is a tough challenge in South Africa spectrum environment at the moment, reasons are that the device is a scarce commodity and not highly dependable.

The Council for Scientific and Industrial Research (CSIR), Google, Tertiary Education and Research Network (TENET), ICASA, and a number of partners on September 2013, conducted trials in TV whitespace in Cape Town [42].

The Dynamic Spectrum Access (DSA) enabled by Geo-location Spectrum Database (GLSD) trials in TV white space (TVWS) was indeed a success in South Africa. The key focus of the trials conducted in TV white space (TVWS) was to help bridge the digital divide especially in remote areas while demonstrating the coexistence of broadband services and the television broadcasting services with minimal interference issues [42].

There were several key findings of the TV white space (TVWS) trials [42], which include:

- The trial produced bit rates of up to $12mbps^2$ broadband connectivity and at a distance of $6.5km^3$

- The geo-location spectrum database (GLSD) technique was implemented and no interference issue during the period of testing was experienced.
- The geo-location spectrum database (GLSD) proved to be an efficient Dynamic Spectrum Access technology during the period of trial.

After the Cape Town TV white space (TVWS) trial which was a success, more trials have begun in the area of TV white space (TVWS). The Department of Science and Technology (DST) announced in July 2013, that a pilot project in the TV white space (TVWS) already begun and this project currently taking place in Limpopo, South Africa. This pilot project is aimed at providing low-cost internet access to the majority of South Africans by 2020 [42].

The Council for Scientific and Industrial Research (CSIR) are at the forefront in Dynamic Spectrum Access (DSA) and Cognitive Radio (CR) research in South Africa. Currently, a Geo-location Spectrum Database (GLSD) that locates available frequencies or channels in the current Analog TV spectrum in South Africa has been created by the Council for Scientific and Industrial Research (CSIR). To build a national Geo-location spectrum database (GLSD), the need to possess blueprints of incumbent national terrestrial television planning model in advance is mandatory. This blueprint will help in the planning and structural composition of the spectrum database.

South Africa belongs to the International Telecommunications Union (ITU) region I, where each television channel spacing utilizes 8MHz of bandwidth [43].The current South African frequency allocation table is provided in [44]. The listed incumbent in the provided frequency allocation table is to be protected using the parameters or protection information provided.

Due to some political setbacks in South Africa, the country is yet to own a TV White Space (TVWS) regulation(s). This setback as such prompted the use of a conservative Minimum Coupling Loss (MCL) approach [45], taking into consideration the 8MHz channel width used in the International Telecommunications Union (ITU) region I, in the design and implementation of a Geo-location spectrum database (GLSD) by the Council for Scientific Industrial Research (CSIR) South Africa. The Minimum Coupling Loss (MCL) approach is simplistic in a way and provides sufficient protection to incumbents in different coverage contours.

This brave step taken by the government of South Africa towards the digital migration and trials in TV white spaces (TVWSs) has given encouragement to other African countries such as Ghana, Tanzania and much more. Currently there are trials in TV whitespace (TVWS) taking place in these countries.

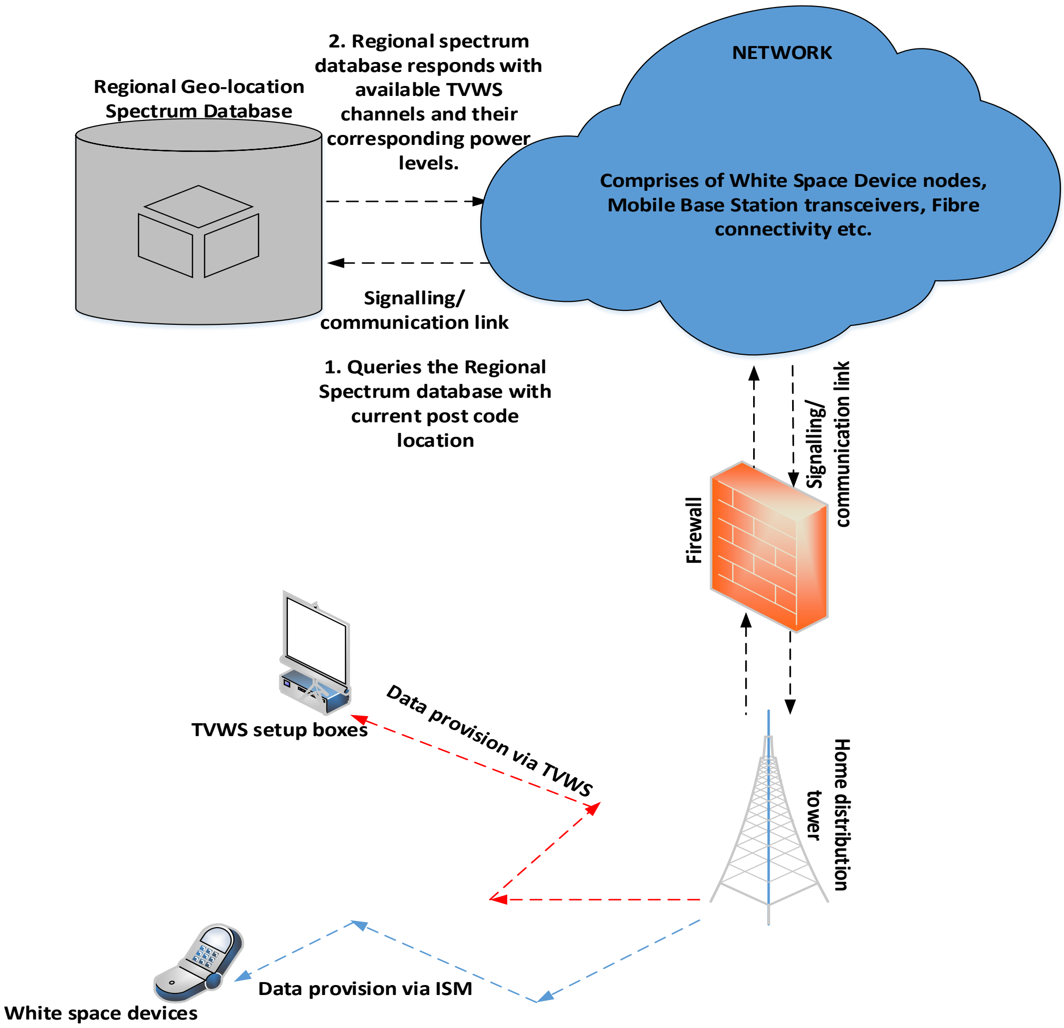

Figure 2.12. A typical Geo-location Spectrum Database (GLSD) setup structure.

Figure 2.12 basically explains the procedure and steps taken in a geo-location spectrum database setup, it also explains the communication channels and signalling that occurs at various nodes and how information received from the spectrum database is being relayed to the individual end terminals or receivers.

2.8 SUMMARY

Spectrum occupancy measurements taken by Independent Communications Authority of South Africa (ICASA) were analysed and key findings from the measurements taken indicates that the under-utilization of spectrum is as a result of the inefficient policies in place and no viable Dynamic Spectrum Access (DSA) technology or mechanism that supports opportunistic use of under-utilized spectrum is in place.

Research conducted in areas of Cognitive Radio (CR) and Dynamic Spectrum Access (DSA) technologies are extensively discussed with major findings in favour of a Dynamic Spectrum Access (DSA) enabled Geo-location Spectrum Databases. The state of the art Cognitive Radio (CR) technology is extensively discussed with focus on Dynamic Spectrum Access (DSA) and how its classification gives rise to strategies on how to implement DSA technology.

Also, a brief description on how the cognitive radio network architecture developed by Akyildiz [20] outlines the three techniques for implementing cognitive radio network in the radio frequency spectrum.

An extensive view on what a white space entails is described with focus on TV white spaces (TVWSs). The benefits of TV white spaces (TVWSs) are discussed and how the exploitation of TVWSs by means of DSA technology for opportunistic use can unlock boundaries in areas of broadband connectivity and enhance development.

Two out of the three known Dynamic Spectrum Access (DSA) approaches are discussed and how these approaches are continuously being evaluated by various sectors/research groups/regulators adopting DSA in order to ascertain the effective approach for roll-out in their respective countries.

The next chapter categorically explains in details the dynamic spectrum access technologies with distinct comparison and view of justifying the research question.

3.0 DYNAMIC SPECTRUM ACCESS TECHNOLOGIES FOR TV WHITE SPACE (TVWS)

According to reports released by Cisco, global traffic is to increase exponentially between 2012 and 2017. Hence, the need for more spectrum to handle such enormous demand is on the high. The migration from Analog to Digital (A/D) transmission is sure to contain the demands for more spectrum but the challenge is what technique or methodology is put in place in order to efficiently manage these enormous demands without causing interference with the existing users. Hence, a common characteristic of cognitive radio is its ability to exploit restricted available spectrum for opportunistic use. There are several important features that constitute the cognitive radio concepts and these features are its capability to sense, measure, learn about its environment and its awareness on specifications related to a radio channel characteristics, local policies, user requirements and other operating restrictions [46]. That been said, more techniques are being developed to enhance and accommodate more traffic with minimal interference. Spectrum sensing is a vital component feature of cognitive radio. It's tasked with obtaining awareness about spectrum usage and the existence of incumbents in a geographic location [46]. This awareness about spectrum usage can be obtained by means of geo-location spectrum database (GLSD), beacon usage, or by local spectrum sensing [46]-[48].These techniques are briefly described and the various setbacks associated with each technique are listed below:

- Spectrum sensing: The CR sensitivity requirement imposed by the regulator must be adhered to for easy detection on the spectrum band.
  Setbacks: It's vulnerable to the hidden node problem. i.e. misdetection problem.
- Geo-location Spectrum Database: The location of a CR is compared to the spectrum database output for safe transmissions.
  Setbacks: Location accuracy, Spectrum database availability, spectrum database maintenance and update.
- Beacon usage: The signal from the Beacon indicates the requested frequencies are available for transmission.
  Setbacks: Beacon failures, speed of updating the beacon and receiving the beacon signal out of desired range.

Each technique or methodology has its own problems and setbacks. Currently, amongst the listed techniques, there are two Dynamic Spectrum Access (DSA) techniques being adopted globally and these techniques are: Spectrum sensing and the Geo-location Spectrum Database (GLSD) technique. The various categories of spectrum sensing are shown in Figure 3.1. [51]

The aim of this section is to highlight several aspects of spectrum sensing with focus on spectrum sensing approaches i.e. local sensing and Geo-location Spectrum Database (GLSD) and challenges associated with both approaches with the view to justify and validate the objectives of the research question. The objectives of the research question is which is a preferred methodology for spectrum management; Geo-location Spectrum Database technique or Spectrum Sensing technique and also a documentation on the methodology used in the experimentation to investigate the problem. There would be some comparison of both techniques and suggestions on which one would be most suitable to meet the demands for spectrum management.

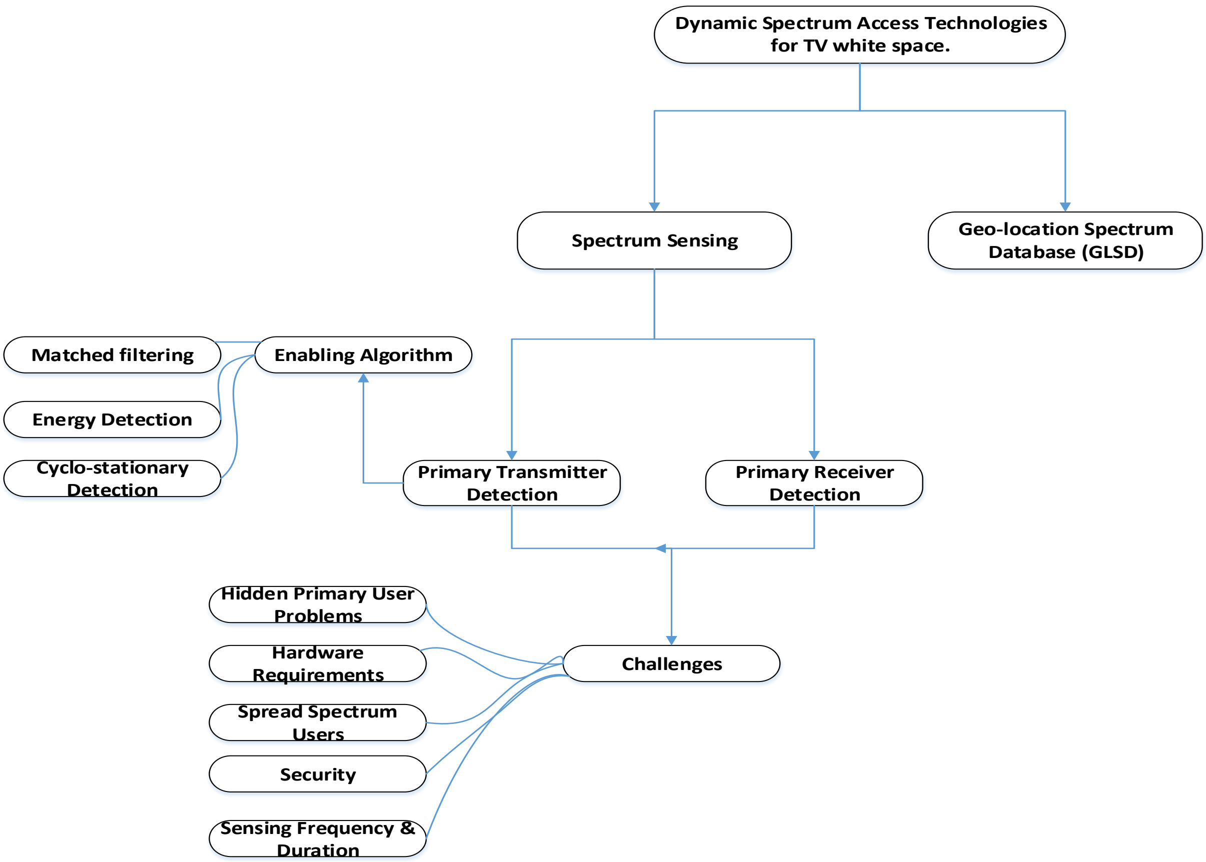

Figure 3.1 Structural compositions of Dynamic Spectrum Access technologies for TV white space exploitation [51].

Before explaining in details the various spectrum sensing enabling algorithm and the challenges associated with spectrum sensing, a multi-dimensional spectrum sensing awareness is briefly explained followed by what spectrum sensing entails and the challenges experienced during implementation.

3.1. Multi-dimensional spectrum sensing

A common conventional definition of a spectrum hole *is "a band of frequencies that are not being used by the primary user of that band at a particular time in a particular geographic area" [52]*. Going by this definition, it primarily entails that spectrum opportunity exists in three or more dimensions of a spectrum space. The commonly talked about dimensions are: frequency, time and geographical space [46].

- Frequency: in this measurement, spectrum opportunity means that not all frequency bands are used concurrently all the time. There are times when some frequency band could be available for opportunistic use.
- Time: in this dimension, spectrum opportunity indicates that the spectrum band is not continuously being used all the time. There are times during the day when the spectrum band could be available for opportunistic use.
- Geographic space: this means that a spectrum band could be available in a certain geographic area while in some other areas it could be occupied at a particular time. This could be as a result of path loss or fading in space.

3.2. SPECTRUM SENSING

Spectrum sensing is a process where a cognitive device continuously scans the RF in three dimensions for spectrum availability without interfering with possible incumbents. For an effective overall system, the cognitive device should be able to spot transmissions, identify these transmissions and make intelligent decisions regarding the situation. It also could be defined as the detection of secondary transmission opportunities and the ability to combine such transmission signals without causing interference and possibly performance degradation at the incumbent receivers.

Hence, this technique over the past few years have come under severe scrutiny because of its unpredicted nature of operation. There are several challenges associated with this technique and these challenges don't favour the implementation of this technique in major countries.

3.3. SPECTRUM SENSING TECHNIQUES

The spectrum sensing techniques commonly deployed in communication systems are outlined in this section. These techniques are: the energy detection technique, the matched filtering detection technique and the cyclo-stationary detection techniques. Recently, there has been so much work done in this area of communication systems in order to enhance interactivity between the CR and its environment. A transmitter detection hypothesis model is defined in [53] and the signals received are modelled by the secondary user as:

$$H_0: X[n] = W[n] \quad if\ PU\ is\ absent$$

$$H_1: X[n] = W[n] + S[n] \quad if\ PU\ is\ present \tag{3.1}$$

where n = 1, 2…, N; the number of samples N, h is the gain of the channel, the additive white Gaussian noise (AWGN) with zero mean is $W[n]$, $S[n]$ is the primary user's signal and it's expected to be a random Gaussian process with zero mean and ∂_x^2 is a variance of X[n]. [53]

Hence, two possible conditions are used to estimate the behaviour of a spectrum sensing technique been used: the probability of detection and the probability of false alarms. The probability of detection is the ability of the cognitive device to correctly discover the existence of an incumbent signal while the probability of false alarms is the ability of the cognitive device to falsely discover the existence of an incumbent signal. The former should be high enough to get an efficient performance while the latter should be low enough to help contain interference [46].

The various spectrum sensing enabling algorithm are described below and how efficient these algorithm. These algorithm or techniques are:

ENERGY DETECTION TECHNIQUE

This technique is the most basic of all detection techniques due to its low computational and implementation complexities but with quite a few flaws [54], [55, and 56]. This technique doesn't require prior knowledge of the primary users signal. Let y[n] be the received form of a signal [46].

$$\boldsymbol{y[n]} \quad = \quad \boldsymbol{s[n] + w[n]} \qquad \textbf{(3.2)}$$

where s[n]is the signal to be detected, $w[n]$ is the AWGN sample and n is the sample index. When $s(n) = 0$, it indicates the primary user is not transmitting. This implies that the decision metric M for the energy detector technique will be expressed as [46]:

$$\boldsymbol{M} \quad = \quad \sum_{\boldsymbol{n=0}}^{\boldsymbol{N}} \quad |\boldsymbol{y[n]}|^{\boldsymbol{2}} \qquad \textbf{(3.3)}$$

where the size of the observation vector is denoted as N. The decision metric (M) is compared with the threshold $\boldsymbol{\lambda_E}$ in order to make a decision on the occupancy of the band.

The observed signal which is the predefined threshold is compared to the output signal of the energy detector and this is used to decide the availability of the primary user on the RF spectrum. If the output signal of the energy detector is higher than the predefined threshold, it indicates the primary user is present but if otherwise, and then the primary user is absent. This is denoted in equation (3.4).

$$\boldsymbol{Energy\ Detection\ (E_D)} \underset{\boldsymbol{A_o}}{\overset{\boldsymbol{A_s}}{\gtrless}} \boldsymbol{\lambda_E} \qquad \textbf{(3.4)}$$

$\boldsymbol{\lambda_E}$ is the threshold. A_SIndicates the primary user is present while A_0 indicates the primary user is absent.The performance of this technique is dependent on two probabilities and they are the probability of detection P_D and probability of false alarm P_F[46].

The flow diagram in Figure 3.2 below explains the operational procedures on the energy detection technique.

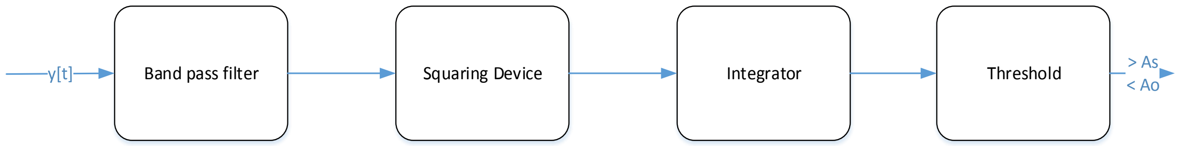

Figure 3.2 Block diagram of an Energy Detector.

According to Figure 3.2, the band pass filter chooses the frequency the user wants to sense. The measurement of the received energy is done by the squaring device. The measured received energy from the squaring device goes through the integrator which is used to evaluate the observation interval, *T*. Now the output received from the integrator *(X)* is then compared to the predefined threshold [46]. If the output received is higher than the threshold, it'll assume a primary user exists on that band but if otherwise, then the band is available for opportunistic use.

Challenges with the Energy detection Technique.

One of the challenges faced with using energy detection technique is the selection of a particular threshold for detecting primary users. This challenge could be addressed by tuning the threshold with respect to the system requirements. Other shortcomings of energy detection include weakness to distinguish between interference, primary users and noise. The noise uncertainty due to the fact that the SNR is below a certain threshold in a practical system hinders the energy detection technique from making an accurate decision. The energy detection is also known for its relatively poor performance under low SNR values [57]. Energy detectors are not efficient enough for detecting spread spectrum signals [58, 59].

MATCHED FILTER DETECTION

A matched filter detector is an optimal linear filter which operates almost the same as a correlation receiver. This detector is used when the cognitive user has prior understanding of the primary signal and where the resulting node aligns with the primary system in order to be able to demodulate the primary signal [60]. This receiver performs perfectly once a secondary user is able to perform a coherent detection of the primary signal [61]. The expression of matched filter detection is given as:

$$\boldsymbol{y}[\boldsymbol{n}] = \sum_{\boldsymbol{k}=-\infty}^{\infty} \boldsymbol{h}[\boldsymbol{n}-\boldsymbol{k}]\boldsymbol{x}[\boldsymbol{k}] \qquad \textbf{(3.5)}$$

The unknown signal 'x' convolves with 'h'. Matched filter detection however is only useful provided the cognitive users have prior information about the primary users. This detection is quite advantageous because it requires less detection time unlike the previous detection techniques [62]. When information regarding the location of a licensed user signal is made available by the cognitive user, only then the matched filter detection is an efficient detector even in the presence of noise. However, if the information about the primary signal is not accurate enough only then the matched filter detector performs inefficiently.

The flow diagram in Figure 3.3 below explains the operational procedures on the matched filter detection technique.

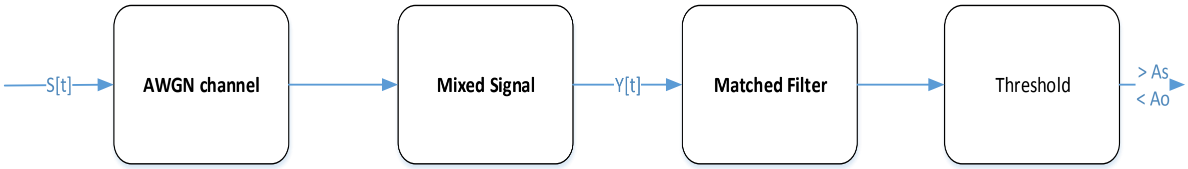

Figure 3.3 Block diagram of Matched Filter detector.

According to Figure 3.3, the received signal from the secondary user *y[t]* is directed into the matched filter and is expressed mathematically as:

$$\boldsymbol{y}[\boldsymbol{t}] = \boldsymbol{h}\,\boldsymbol{s}[\boldsymbol{t}] + \boldsymbol{w}[\boldsymbol{t}] \qquad \textbf{(3.6)}$$

The timed reversed version of the known signal being convolved is equivalent to the received matched filter signal [63].

$$y[t] * S(T - t + \tau) \qquad (3.7)$$

T is the symbol duration and τ is the shift in the known signal. The matched filter output is then correlated to a threshold factor in order to ascertain the location of the primary user on the band [63].

Challenges with the Matched filter detection technique

When the matched filter is being implemented to detect spectrum holes, the occurrence of continuous multiple primary user signals at the same time over the same bandwidth can influence the accuracy of the filters decisions. However, due to these constraints and complexity, it certainly has affected the adoption of a matched filter detection for Dynamic Spectrum Access (DSA) [64].

From a complexity point of view, it is quite complex to implement but it’s got the highest level of accuracy. Due to its complex nature i.e. several receiver structure algorithms, it requires a high power consumption in order for detection to occur [46]. It really does consume more power.

CYCLOSTATIONARY DETECTION

This feature detection method involves sensing incumbent user signals by taking advantage of the characteristics cyclo-stationary structure of the signal being acquired [46, 58, and 65]. The cyclo-stationary feature detection takes advantage of the periodicity in the acquired incumbent signal in order to sense the presence of incumbent users. The periodicity is usually located in features which include sine wave carriers, pulse trains, hopping sequences, repeating spreading and cyclic prefixes of the primary signal [58]. This detector tries to take advantage of imposed periodic signals which could be caused by modulation, cyclic prefix or probably signals that are inserted in order to enhance synchronization, channel estimation or equalization. These signals could be displayed as a cyclo-stationary random process [63].

The main advantage the cyclo-stationary detector has over the other detectors is its ability to distinguish between specific types of primary signals, interference and noise. It's practically more efficient than energy detection in low SNR regions. However, its vulnerability to model uncertainties, high computational complexities, longer sensing time, channel fading effects and sampling clock offsets are quite alarming [66, 67]. This vulnerability at some point affects its detection performance.

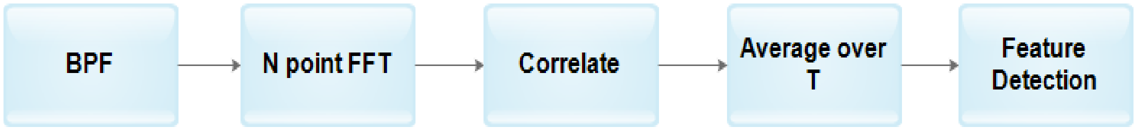

Figure 3.4 Block Diagram of a cyclo-stationary feature Detection.

According to Figure 3.4, this involves a band pass filter, finding the fast Fourier transform, correlating, averaging and feature detection. Final output of the CFD section is the estimated cyclic spectral correlation function (SCF).This spectral correlation function is analysed to detect the signals in the cyclo-stationary-based spectrum sensing method [68].

WAVELET DETECTION

This form of detection offers more flexibility and simplicity when deployed on wideband signals. It primarily detects spectrum holes in a spectrum band by treating the entire spectrum band as a sequence of frequency sub-bands [69]. The power characteristics present in each frequency sub-band only changes suddenly on the edge of the next frequency sub-band [69]. Spectrum holes are detected by observing the singularities in the results obtained [70]. Figure 3.5 depicts the wavelet detection procedures for wideband spectrum sensing.

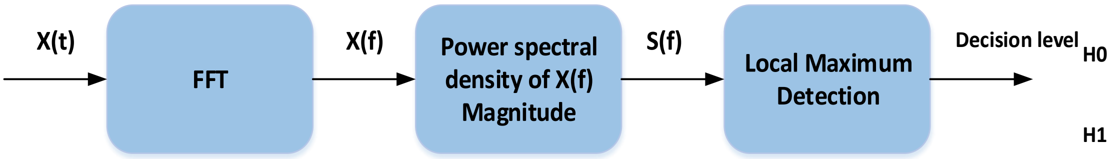

Figure 3.5 Block diagram of a wavelet detection

3.4. PERFORMANCE METRICS COMPARISON BETWEEN THE VARIOUS SPECTRUM SENSING TECHNIQUES.

The above mentioned spectrum sensing enabling algorithm or technique has certain advantages and disadvantages when compared against one another. A few enabling algorithm perform perfectly well on licensed spectrum while some don't. The same applies to unlicensed spectrum. The qualitative analyses of the explained enabling algorithms are described in Table 3.1 below:

Table 3.1 Qualitative analysis of the different enabling algorithms

Enabling Algorithm	**Advantages**	**Disadvantages**
Energy Detection	• It performs efficiently at high SNRs. • It doesn't require prior information of PUs. • It has a low computational complexity level.	• It's less efficient in areas with low signal to noise ratio (SNR) and difficulties differentiating PUs and SUs • Does not perform on spread spectrum signals • Difficulties in selecting detection threshold.
Cyclo-stationary detector	• Efficient in areas with low signal to noise ratio (SNR), high SNRs and robust against interference. • In terms of accuracy, it provides high level of accuracy in results.	• For efficient performances, information on the location of PUs must be provided. • Relatively high computational complexity
Matched filter detector	• Best performance level at all SNRs provided it has knowledge of the PU or SU.	• Requires information on the location of PUs. • It has got a high level of computational complexity in terms of implementation.

	• Transmitting characteristics is chosen to improve its accuracy and performance. .	• Poor performance if no information about the PUs or SUs is provided. • Requires perfect information about the PUs or SUs.
Wavelet detection	• Efficient when deployed on wideband spectrum sensing. • Performs efficiently at all SNRs.	• Very high complexity. Not simple to implement.

Hence, it is quite obvious from the outlined advantages listed in Table 3.1 that the energy detection is a more convenient approach for unlicensed bands as it doesn’t need prior information on the location of PUs.

3.5. INSTABILITIES AND CHALLENGES OF SPECTRUM SENSING

Developing an algorithm or methodology that correctly checks the sequence at which a cognitive user vacates and occupies a channel where the level of occupancy is high and a limited number of channels are available is a very vital issue and must be treated with caution else it could render an entire system inoperable.

A practically familiar scenario is where the channel occupancy is quite high and a limited number of channels are available. Now the first cognitive user probably has settled in, only for it to sense another primary user which implies it must vacate that channel for another available channel. Furthermore, the next channel could go through possibly the same sequence as the previous. This sequence would be continuous till it reaches the final user, and this user moves into the first channel and the sequence is repeated once again [71].

However, developing an algorithm that can manage and check these sequences would require a sophisticated hardware in place to be able to execute such algorithm and this eventually narrow down to the challenges experienced in the implementation of spectrum sensing technique. These challenges are quite a drawback to spectrum sensing and primarily the reason most countries are yet to fully embrace it as a Dynamic Spectrum Access technology (DSA) for exploiting TV white spaces (TVWSs). These challenges are highlighted below:

- Hardware requirements: There are certain hardware requirements that terminals must possess in other to be able to perform spectrum sensing over a much wider band in order to be able to utilize spectrum opportunities that presents itself. Hardware requirements such as high sampling rate, high speed signal processors and high resolution Analog to Digital (ADCs) converters with large dynamic range etc. However, this is usually not the case as most cognitive radio terminals are short of these standards, thereby not being fitted to acquire and analyse a much larger spectrum band which invariably results to loss of spectrum opportunity [46]. The single radio and dual radio architecture are the two architecture associated with spectrum sensing [54, 72]. The former has a simplistic approach which is relatively cheap to implement but low level of accuracy while the latter can transmit, receive and monitor the spectrum band simultaneously but consumes a lot of power and its quite complex to implement [46].

- Hidden node problem: Several factors such as severe multi-path fading i.e. fading due to obstruction of signals or collision of signals experienced by opportunistic users while sensing for incumbent transmissions [46], could cause the hidden node problem. Figure 3.6 depicts a scenario of a hidden node problem. The circles indicate the regions of both the primary user and cognitive user. The cognitive device signal causing interference to the primary receiver as it's unable to locate the primary transmitter signal due to an obstruction [46].

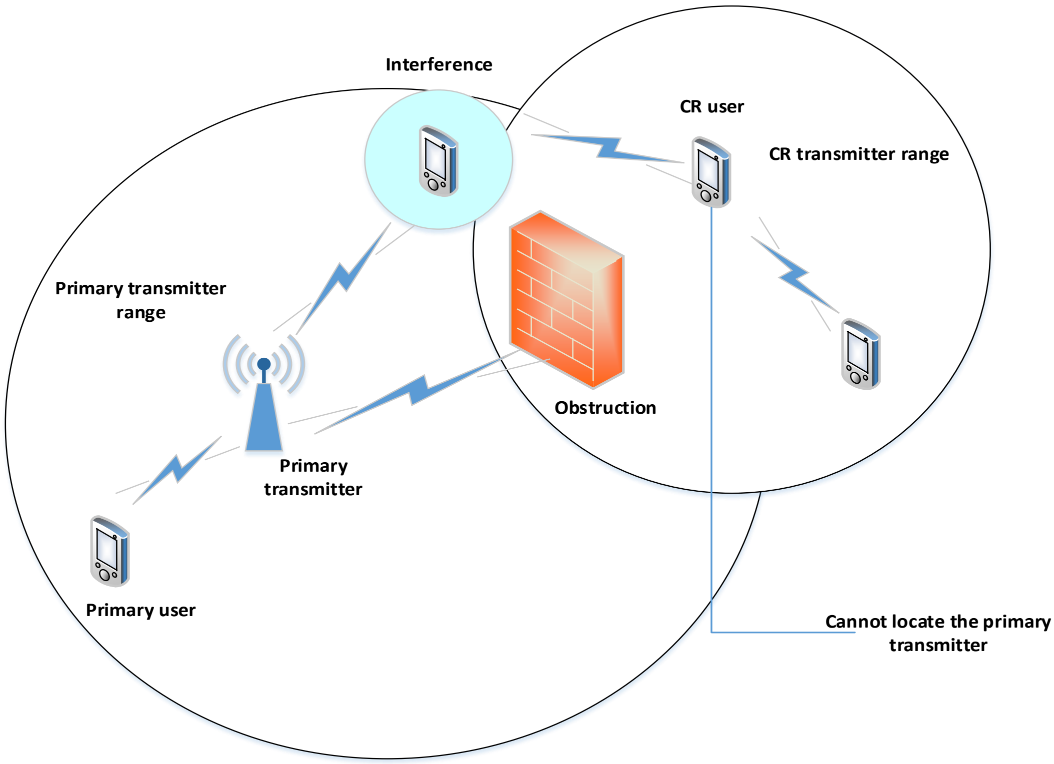

Figure 3.6 Scenario of hidden node problem [46].

- Detecting spread spectrum primary users: The spread spectrum and fixed frequency are the two technologies that exist for commercially available devices. The spread spectrum technology can be categorized into Frequency-hopping spread spectrum (FHSS) and Direct-sequence spread spectrum (DSSS) [46]. However, the IEEE 802.11 a/g based wireless local area network is an FHSS device which operates over a single frequency and has the ability to switch to multiple narrowband; this characteristic feature is called hopping. While the DSSS devices operates similarly, but spread their energy over a single band [46]. It is quite difficult to sense primary users using spread spectrum signalling because of its evenly distributed power over a wide frequency [46].

- Sensing duration and frequency: Opportunistic users are to immediately vacate a frequency band upon an incumbent's arrival. In other words, the opportunistic users are to leave the band for the primary users so as to avoid interference issues. Hence, the implemented sensing algorithm should be efficient enough to detect the primary signals or users within a specific time or duration. This criterion limits the performance of the sensing algorithm as more time is spent on sensing rather than effectively utilizing spectrum opportunities. This invariably results to challenges in cognitive radio design. The selection of hardware parameters for sensing results in a trade-off between how quick the radio frequency spectrum is sensed and how reliable the sensed results are [46].

- Security: Cognitive Radio users are prone to malicious attack such as the Primary User Emulation (PUE) attack [73]. In this sort of invasion, a malicious user re-configures its air interface and poses as a primary user. The more challenging part to this security issue experienced is developing an effective counter measures to subdue an attack made on the primary user. In [74] a proposed solution which suggests the use of a public key encryption based primary user identification which stops secondary users from posing as primary users was discussed.

The challenges and instabilities experienced when implementing the spectrum sensing technique however comes with a severe scrutiny. These challenges explains the reason why regulators such as Office of Communication (Ofcom) UK and the Federal Communications Commission (FCC) US, out-rightly declined the use of only spectrum sensing approach for exploiting TV white spaces [30, 39]. Although more research on how to mitigate the challenges experienced are in progress and also more Dynamic Spectrum Access technologies are being developed as an alternative approach i.e. Geo-location Spectrum Database (GLSD).

3.6. GEOLOCATION SPECTRUM DATABASE APPROACH

A Geo-location Spectrum Database is a Dynamic Spectrum Access (DSA) technology. It's also a repository which stores information on the availability of spectrum holes or white spaces. This Dynamic Spectrum Access (DSA) technology enables the opportunistic use of spectrum. The information stored in the spectrum database is recorded in form of location (or pixels), emission power levels, frequency range, time, etc. The accuracy of this information will enable efficient spectrum usage without causing harmful interference to incumbents.

In this approach, the primary user is registered on a database. The opportunistic user will have to first determine its location and then interrogate the database periodically in order to find free and available channels. Geographical location of a secondary user device within an exact point is very vital. Other information such as device type, model and expected area of operation are to be provided to the database via a secondary user device. In response, available frequencies, maximum transmission power and if the secondary user device could consult other national or regional database is provided [75].

With this approach, the need for either the regulator or operator to build and maintain such databases arises. The need for a reliable communication channel for exchanging information between the CR device and the geo-location database before a TVWS link is used is one of the main problems with the geo-location database technique. One suggested solution is the use of GPS for outdoor operation and an internet connection for indoor operation. A geo-location spectrum database will be used to alert the WSDs on the available channels. A master-slave configuration for WSDs is envisaged: the master connects to the spectrum database and the slaves are managed by the master, i.e., they do not access the database. The procedure is as follows: the service provider provides a "master" device with a table of particular spectrum databases, then the opportunistic user will select a database from the provided table and forward its location and communication parameters [31]. In this manner, the spectrum database will respond to the WSD with a table of channels that are currently available for opportunistic use and their corresponding characteristic parameters. To compute the available channels, the spectrum database needs to be mindful of primary licensed usage of the spectrum and better stick to the protocols set out by the service providers [31]. The master WSD will deliver the available white space table to the suitable slave devices. This configuration reduces signalling overhead in database access.

South Africa is geographically divided into three regions and they are namely: the central region, northern region and southern region. Going by the Council of Scientific Industrial Research (CSIR) spectrum database structure in South Africa, there are several regional spectrum database designed with respect to a particular region and all these regional spectrum databases all link up to a master spectrum database. The reason as to why several regional databases are setup is to reduce signalling overhead and avoid excess traffic directed towards the master database. Structural positioning of a spectrum database designed by the CSIR South Africa [76] is illustrated in Figure 3.7.

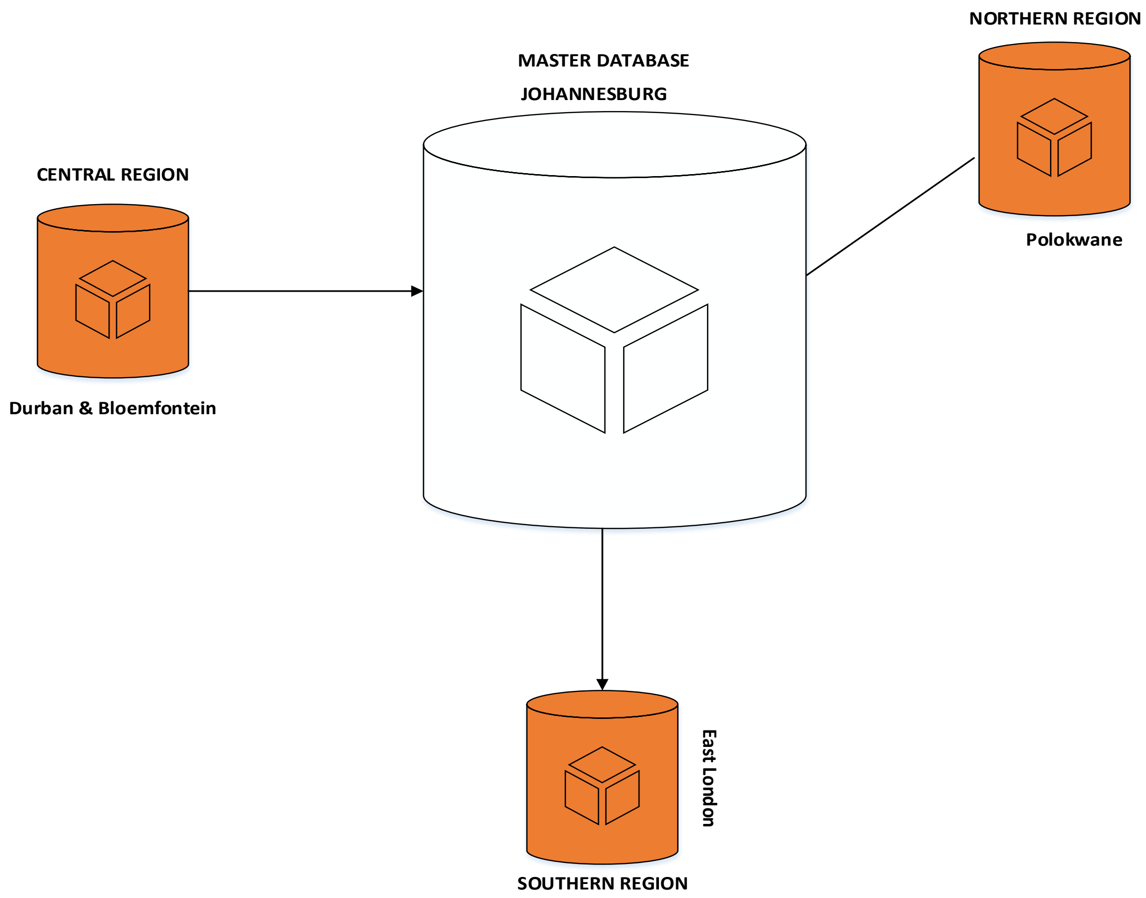

Figure 3.7 Typical Geo-location Spectrum Database structure in South Africa [76].

3.6.1. CSIR Geo-location Spectrum Database Administration

The scheduled migration from analog to digital transmission as proposed by the International Telecommunications Union (ITU) is yet to fully commence in South Africa and as a result of this delay, the Independent Communication Authority of South Africa (ICASA) is yet to make available a functional and approved TVWS regulation and geo-location spectrum database administration. In the meantime, the CSIR are responsible for the spectrum database administration being created on the behalf of ICASA. The master spectrum database is located at the CSIR head office in Gauteng, the rest of the regional spectrum databases are located at various regional offices of the CSIR in South Africa.

3.6.2. CSIR Geo-location Spectrum Database (GLSD) access

A physical optic fibre connection is used to link all regional spectrum databases to the master database. Only ICASA approved fixed white space nodes are allowed to query the spectrum database. The several ways to gain access to the CSIR spectrum database are listed below:

- Basic communications end-user devices such as laptops, tablets etc. would need to connect to the web in order to query the spectrum database with respect to its location for available channels.
- The communication between the end user device and spectrum database is made possible through a signalling channel to the white space nodes, these nodes interacts with the regional database on the behalf of the user device by requesting for available channels for opportunistic use.

A graphical example of the communication processes such as the signalling links between the spectrum database, white space device nodes, base stations and end user terminals are expressed in Figure 2.12 on page 40.

3.6.3. GLSD ARCHITECTURAL SCOPE & PERFORMANCE.

The database includes three types of information and the information is as follows [1, 31]:

- Region and network of secured facilities recorded in the regulator commission's consolidated database system (CDBS) and universal licensing system database (ULS).
- Region and network of secured facilities not recorded in the regulator's database systems.
- Information about Region and detection of secondary WSDs (geographic location, regulator's serial ID number, responsible person information).

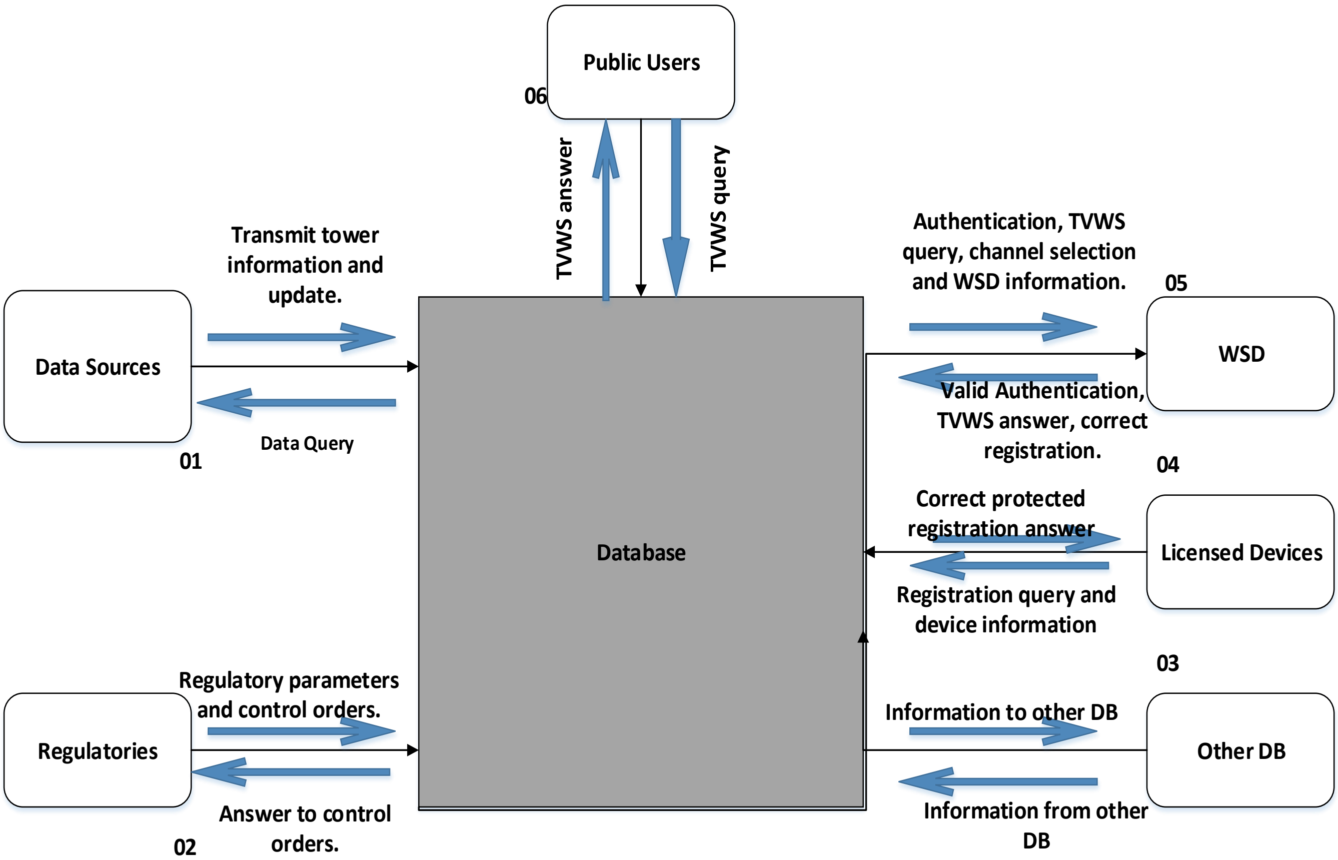

Figure 3.8 Diagram of a spectrum database structure and performance [1].

Database: This hoards and exploits the data suitable to detect the available channels in a location and at a particular time. Necessary readings are carried out to determine available white spaces with help of some data from the repository.

Data Sources: In this section, the information about the presence of licensed users is provided by the data source. The information provided is stored in the spectrum database. Though this data must be supplied by the official or regulated data sources.

Regulatory: Just as FCC does the regulatory rules in the USA, some regulatory entity such as ICASA in South Africa ought to have oversight over the set-up of a spectrum database system. These regulations make certain that the spectrum database system strictly adheres to the recognized policy or proceedings so as not to incite interference on incumbent users.

Other Database: Ability of a master spectrum database to synchronize with each other regional spectrum databases makes it far easier for the registration of not registered licensed users, and information sharing between databases is vital for this to occur.

Licensed devices: Particularly, most licensed devices are registered via the official source. Consequently, the non-registered licensed users can be granted access to the spectrum database to sign up.

White Space Device (WSD): All WSDs wanting access to available TVWS must first sign up and identify with the database before requesting for available white space channels.

Public Users: Public users should be granted connection to the spectrum database at a given location and time in order to get information even if they are not going to make use of it.

A typical TVWS database is shown in Figure 2.5 & 2.6 on page 22. The national regulator can decide to either own or contract out the supply of a central spectrum database, and several secondary or regional spectrum databases may be owned by network operators.

3.6.4. ADVANTAGES OF GLSD TECHNIQUE OVER SPECTRUM SENSING TECHNIQUE

Spectrum scarcity or rather spectrum underutilization has been a lingering issue for the past few of years. Techniques such as the spectrum sensing technique has existed for quite some time now but due to the instabilities experienced while deploying this technique not only made it unstable but also not a trusted technique. The advent development of the Geo-location Spectrum Database (GLSD) has not only proved that the wait is over but also promises to significantly reduce spectrum inefficiency and increase spectrum utilization. This new technology is often compared to spectrum sensing in areas of spectrum management and utilization. However, an analysis from a technological view as to why the Geo-location Spectrum Database (GLSD) technology is more efficient than the spectrum sensing and the likely setbacks encountered when deploying both technologies are explained below.

The advantage(s) geo-location spectrum database has over spectrum sensing includes:

- Geo-location Spectrum Database (GLSD) technique provides more protection and accuracy to licensed users than using stand-alone spectrum sensing technique. The reasons being that the geo-location does not need to sense the RF spectrum for incumbents because it’s already aware of their location with the help of a Global Positioning System (GPS) unlike the spectrum sensing technique that requires sensing the RF spectrum from time to time.

- In terms of spectrum utilization efficiency, geo-location enabled white space devices (WSDs) will effectively utilize white space spectrum more than spectrum sensing enabled white space devices (WSDs) because the geo-location spectrum enabled white space devices are able to determine protected service contours while the spectrum sensing enabled white space devices would need to sense primary signals at a very low power levels in order not to experience hidden node effects or multi-path fading as the case may be.
  White Space Devices (WSD) continuously communicates with the geo-location spectrum database in order to avoid harmful interference with incumbents.

- Sensing only WSDs must sense incumbent signals down to very low levels in order to fight hidden node effects and others local sensing defects such as shadowing and fading effect. The geo-location spectrum database already doesn't have to go through such because it can accurately locate protected service contours for each station.

- Portable sensing only units are prone to low antenna heights and probably low antenna gains, all these eventually makes sensing incumbent signal much more of a task and requires lower incumbent detection threshold.

- Depending on how the configuration and setup looks like, most WSDs are configured to consult the geo-location spectrum database (e.g. hourly) to obtain incumbent transmitter updates for the band. This feature not only creates the need for field interference issues to be sorted out by regulators but also creates dynamism.

- Talking about dynamism, the geo-location spectrum database is readily adaptable to changes in services. More like trying to program service priorities into a spectrum database so that it gives privileges to both licensed and unlicensed devices in an orderly manner.

3.6.5. BENEFITS OF BUILDING ON A SPECTRUM DATABASE

There are quite some benefits that come with the spectrum database. These benefits are stated below:

- The possibilities of having stranded users are so minor. Any band can be listed and then de-listed. It's all about the dynamism that was mentioned earlier on.
- Access to each band is restricted based on operating conditions. This implies that criteria must be strictly adhered to before granted access to the band.
- Pre-emption, shutdown and privilege access helps protect primary operations.
- It also creates a platform to enable secondary markets. A well-managed opportunistic access of the geo-location spectrum database is capable of enabling such platform.
- It also ensures more efficient use of the spectrum.
- It gives room for more competition and innovation.

3.6.6. SETBACKS OF BUILDING ON A SPECTRUM DATABASE

There are quite some concerns with building on a spectrum database. These concerns actually question the reliability of the spectrum database. The various concerns are listed below:

- Location accuracy of the spectrum database
- Spectrum database availability
- Spectrum database maintenance
- Spectrum database update.

However, these various setbacks could easily be tackled by imposing an efficient regulatory policy. The policy should include the setup, building and availability of a spectrum database be offered to private sectors, rather than the regulators handling such operations. This way, it creates room for competition in terms of quality of services being offered. By so doing, concerns with respect to spectrum database update, availability and maintenance are sorted depending on the structure of the policy on ground.

Having discussed the basic and structural composition of a geo-location spectrum database technique and its added advantage over spectrum sensing technique. Based on comparison, the advantage the geo-location spectrum database technique possesses over spectrum sensing technique certainly outweighs its disadvantage. This primarily is the reason most developed countries adopting the Dynamic spectrum Access (DSA) technology would opt for a geo-location spectrum database implementation.

3.7. SUMMARY

An introduction on Dynamic Spectrum Access technologies was explained in this chapter with focus on spectrum sensing and geo-location spectrum database. A detailed explanation on the enabling algorithms to the spectrum sensing technique was also discussed, challenges and instabilities associated with this technique was expressed in details.

The energy detection enabling algorithm methodology that was used in the experimentation was also explained in details. This methodology is quite cheap to implement and it's mostly used in areas of research. The geo-location spectrum database structure for dynamic spectrum access in South Africa was analysed, the structural composition on implementation of a spectrum database was discussed. A comparison between the spectrum sensing approach and geo-location spectrum database was discussed and conclusions based on performance and spectrum utilization was in favour of the geo-location spectrum database technique.

Countries such as the United Kingdom who have adopted the Dynamic Spectrum Access (DSA) technique would rather go for a technology that would yield more return on investment and the geo-location spectrum database technique currently is that technique that is dynamic enough to efficiently manage the spectrum and co-exist with other emerging wireless technologies with minimized interference level. However, it's still a new technology that is open to modifications.

Based on the analysis discussed in this chapter, the geo-location spectrum database offers more in areas of spectrum utilization and performance but in terms of rollout it offers less because much standardization is required to set up a geo-location spectrum database. While the spectrum sensing approach is easily implemented (energy detection), it's not guaranteed to provide the required support in terms of proper detection of primary users. This however results into the implementation of a more complex and reliable spectrum sensing technique which possibly requires efficient hardware for rollout and ultimately comes at a higher cost of implementation.
Hence the experimental approach which demonstrates how efficiently the spectrum is being utilized using both dynamic spectrum access technologies was demonstrated in the next chapter and conclusions were deduced from the outcomes obtained from using both technologies.

4.0 DYNAMIC SPECTRUM ACCESS USING GNURADIO AND GEO-LOCATION SPECTRUM DATABASE (GLSD) IMPLEMENTATION.

Opportunistic access of the RF spectrum requires the incumbent users be protected from harmful interference from the secondary or opportunistic users. A parallel scenario to consider also is that these opportunistic users need to be guaranteed some quality of service considering the fact that they have to avoid interfering with incumbents and they do not possess a dedicated bandwidth of their own. To address this, two Dynamic Spectrum Access (DSA) technologies have been proposed, the spectrum sensing technique and the geo-location spectrum database technique. An introduction to Dynamic Spectrum Access technologies have previously been explained in details in the previous chapters. A functional geo-location spectrum database was created and used to implement opportunistic access of the radio frequency spectrum. Spectrum sensing equipment such as the Universal Software Radio Peripheral (USRPs) was also made available for this implementation.

The structure of this chapter started off with a brief introduction on the Dynamic Spectrum Access methodology using spectrum sensing and geo-location spectrum database. Then the system architecture which comprises of the structural setup and functional overview used to implement DSA methodology was presented. The experimental platform which constitutes the terminal, open source software and test bed was described.

The spectrum sensing algorithm used to implement dynamic spectrum access was discussed. In this case, the energy detection algorithm or technique was used because of its relatively cheap implementation and practicality. The trade-offs and performances experienced while demonstrating the spectrum sensing and Geo-location Spectrum Database techniques were discussed. The results from the spectrum sensing implementation were interpreted.

The whole structural process for DSA was then repeated but this time it was done using a geo-location spectrum database. Results, conclusion and future work were also suggested.

4.1 METHODOLOGY FOR SPECTRUM SENSING TECHNIQUE

This section briefly describes the methodology used in the demonstration of Dynamic Spectrum Access (DSA) using the spectrum sensing technique. This research work comprises of a standard research methodology. A quantitative, qualitative and experimental approach was employed in order to answer the research question of "*which is the preferred methodology to spectrum management; a spectrum database or spectrum sensing technique*".

The composition of this work started with a well-documented literature survey on CR, Geo-location Spectrum Database (GLSD) and Dynamic Spectrum Access (DSA). After getting familiarized with the ethics of both techniques through related work done, journals etc., the necessary information acquired was narrowed down to focus more on the objectives of this research work.

The most vital part of any cognitive radio is its intelligence to adapt and utilize any given opportunity (in terms of spectrum availability) in an efficient way. The white spaces should be located with little information about the spectrum as it's quite a task to consider all dimensions of the radio spectrum while sensing for white spaces.

A brief and qualitative study on the available enabling sensing algorithm was described in the previous chapter. For the experimental analysis, the experiment was conducted in two different locations and during peak hours. A wideband spectrum sensing was performed with more emphasis on the TV broadcast frequency, 16 MHz of the TV broadcast frequency bandwidth was sensed (474-490 MHz). Results from post processing on MATLAB of both locations were obtained and compared. Spectral plots and spectrogram plots showing activities on the spectrum band were plotted from the data collected. The spectrogram plot primarily shows available white spaces present on the frequency band. While the quantitative analysis which includes functional and structural composition of the experiment, a test-bed with terminal called the USRP2 running GNU Radio is interfaced with a PC running Ubuntu was used for the implementation. The energy detector or power detector was considered the most simplistic approach for the implementation. The algorithm was implemented over the test-bed set-up and results gathered in the form of raw data were processed. The experimental procedures are discussed while the results obtained are tabled in the next section.

4.2 EXPERIMENTAL PLATFORM

This section describes the components and platforms used in the experiment and the hypothesis implemented in getting the results

4.2.1. GNU Radio

GNU radio software is open source with several attributes which includes ability to build several communication systems. When a software is said to be open source, it simply implies open access and free to download. The GNU radio software primarily is a software define radio commonly used in academic and certain commercial environments in assisting wireless communications research. GNU radio also consists of top blocks which are majorly encrypted in Python programming language, signal processing path which is being executed in C++ programming language and some other basic library functions [77, 78]. The signal processing blocks library can be implemented using a low cost RF hardware e.g. USRP, which allows for creation of software define radios [79].

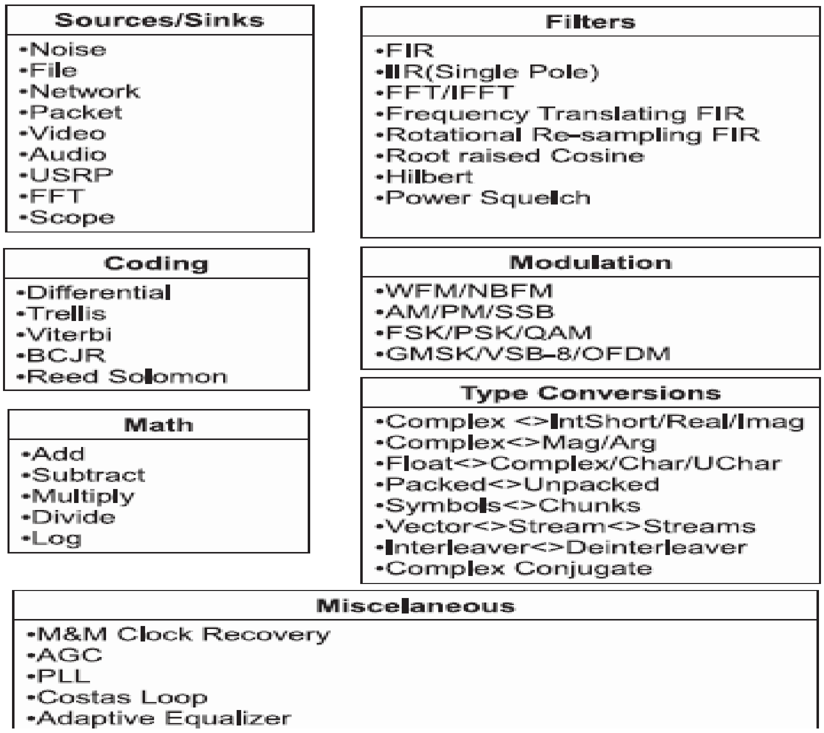

Figure 4.1 GNU Radio libraries and modules [77].

These signal processing blocks are programmed in C++ while Python acts as bridge between processing blocks. i.e. enables communication between blocks which constitutes a Python flow graph. The link between the signal processing block in C++ and Python can be used to deploy the baseband part of a software defined radio [77, 80] which is described in Figure 4.2.

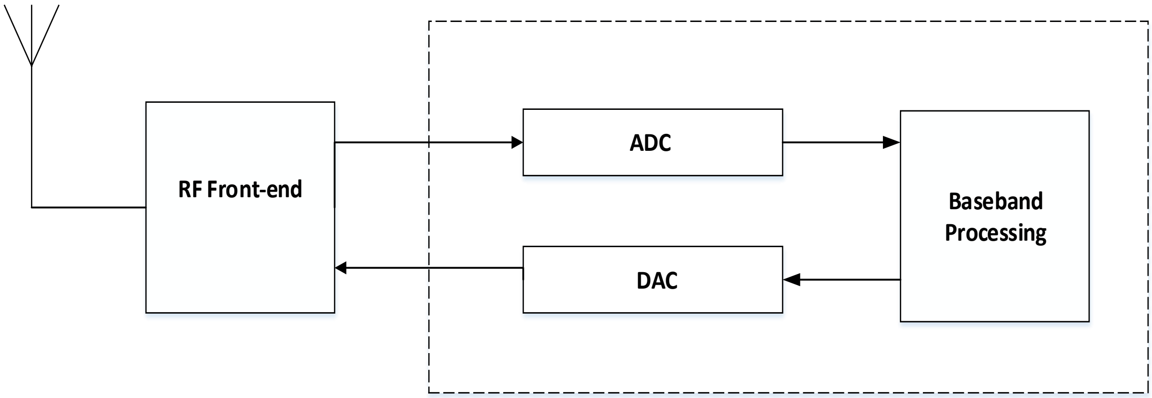

Figure 4.2 Block diagram of a Software defined radio (SDR) [80]

SWIG wraps the C++ libraries into codes to enable smooth operation with the Python scripting language The USRP and GNU radio together provides an interface where applications/programmes could easily be tested. The USRP terminal is the physical link between the baseband signal processing blocks and its environments. It converts analog value of the frequency spectrum to its digital domain and vice-versa [80].

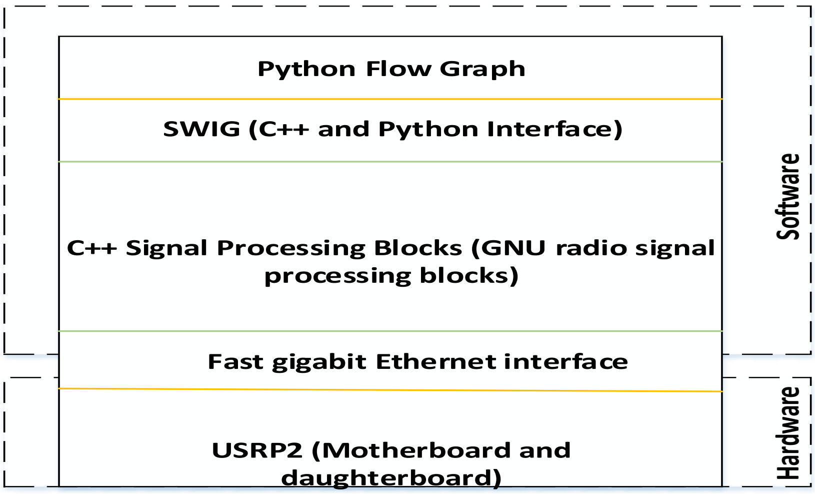

Figure 4.3 Structures of an SDR and USRP [80]

Figure 4.3 depicts the structure of GNU Radio and USRP SDR. The USRP2 will convert down and marginalize the inflow data from the air and passes it to the GNU Radio through the fast gigabit Ethernet interface. The received signal is filtered and demodulated to a packet or stream of data.

4.2.2. USRP STRUCTURE AND OVERVIEW

The Universal Software Radio Peripheral (USRP) is a flexible low cost platform for software defined radios (SDR) developed by Matt Ettus [81]. Technically, the USRP was built to assist researchers and developers who have got limited access to resources and would want their ideas to be implemented. The USRPs are of two types, the USRP1 and USRP2. However, the major difference between both is that the USRP1 can manage from 1-250MHz in terms of receiver and transmitter frequency and its port access is USB while the USRP2 uses a fast gigabit Ethernet port and can manage from 50-2.2GHz in terms of receiver and transmitter frequency [81]. Generally, they consist of two main board types, the motherboard and the daughterboard. The motherboard consists of four 12-bit Analog to Digital Converter (ADC) with sampling rate up to 64MS/s, four 14-bit Digital to Analog Converter (DAC) with speed up to 128MS/s, two Digital up Converter (DUC) to up convert the baseband signal to 128MS/s before translating them to the selected output frequency and is shown in Figure 4.4. [82].

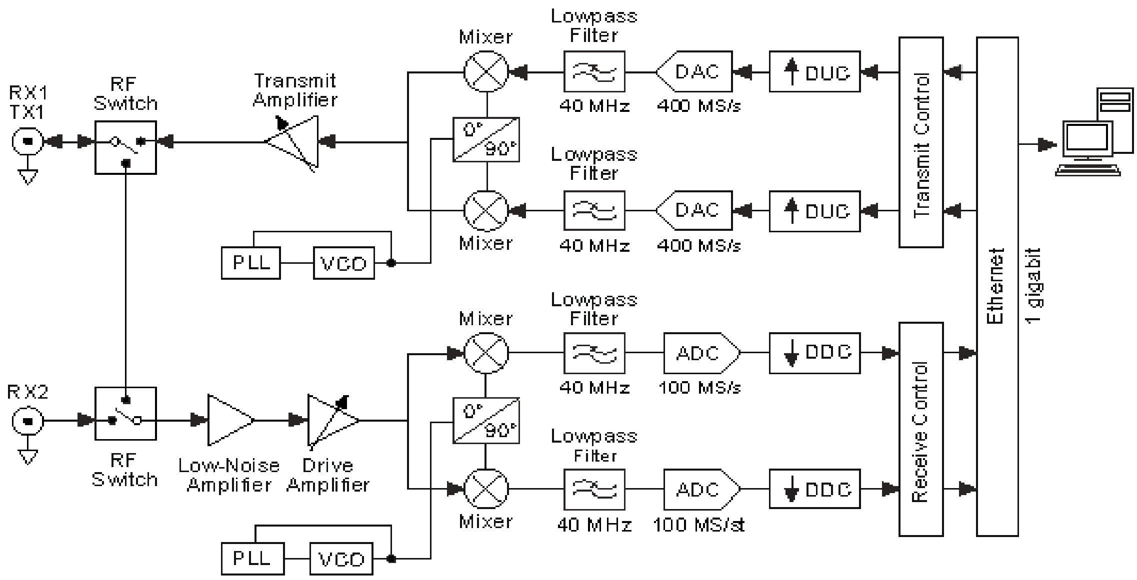

Figure 4.4. Block diagram of a USRP Motherboard [82].

Receive Path (RX) of the USRP

The structural composition of the RX path in the USRP is briefly explained in Figure 4.5. First, the frequency of the received signal from the radio frequency (RF) spectrum is down-converted by the Digital Converter (DC) into an intermediate frequency before its being forwarded to the analog-to-digital converter (ADC) [77]. After the messages have being received, it is then sampled at 64 Msps (mega samples per second) which is the default setting in the USRP. After sampling, it is then forwarded to the Field Programmable Gate Away (FPGA). In the FPGA block, residual frequency down conversion and rate conversion is done there. In other words, the signal from the intermediate frequency is down-converted while the signal samples are decimated in a way that the data rate is easily adapted for efficient performance output between the Ethernet interface and the PC computing ability [77].

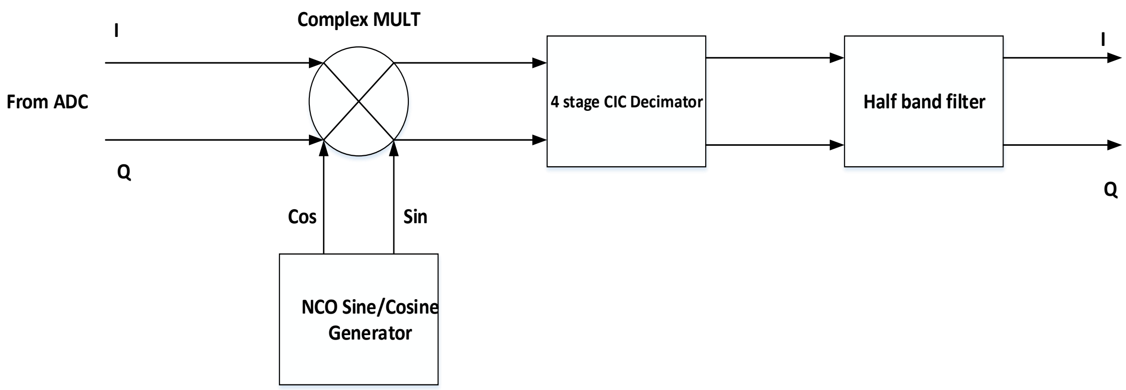

Figure 4.5. Structural diagram of a Field Programmable Gate Away (FPGA) Digital Down-Converter (DDC) [77].

Transmit Path (TX) of the USRP

In the transmitter path (TX), the logic behind the RX path is applied to the TX path, only this time it is done in a reversed manner. i.e. reverse engineering. The interface between the Software Define Radio (SDR) and the USRP which in most cases is a fast gigabit Ethernet port, is the link used in transmitting complex baseband signals into the USRP. Interpolation and up-conversion of the received signals into an intermediate frequency takes place in the

Digital Up-Converters (DUC) then processed through to the DAC where it is converted back into analog and then forwarded to the RF board [80].

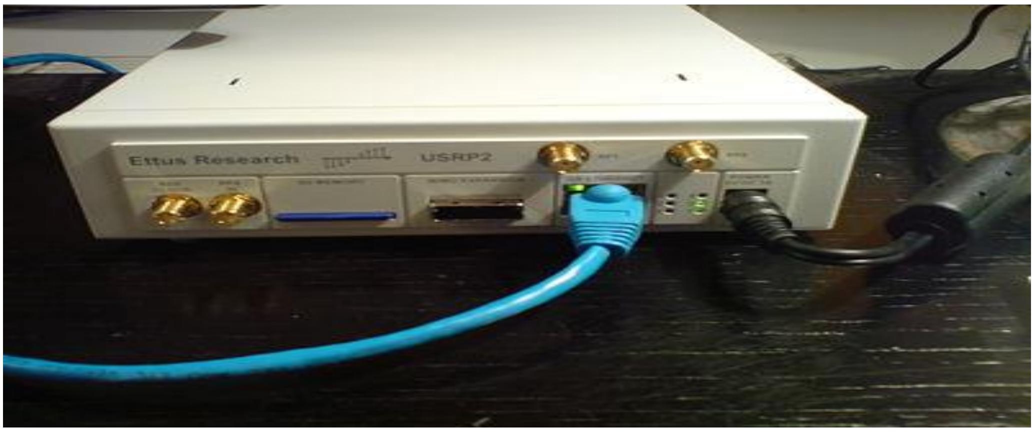

Figure 4.6 USRP2

Figure 4.6 is the USRP2 terminal box with a fast gigabit Ethernet port on display. The USRP1 uses a USB connection to connect via a host computer while the USRP2 connects via a fast gigabit Ethernet port to a host computer and can handle a maximum bandwidth of 25MHz. The basic differences between the USRP1 and USRP2 are expressed in Table 4.1. [81, 83]

Table 4.1 Differences between the USRP1 and USRP2 [83].

	USRP1	**USRP2**
Interface	***USB 2.0***	***Gigabit Ethernet port***
Field Programmable Gate Away (FPGA)	***Itera EP1C12***	***Xilinx Spartan 3 2000***
RF Bandwidth to/from host	***8 MHz at 16bits***	***25 MHz at 16bits***
Cost	***$700 (this price varies with respect to specs)***	***$1500 (Price vary with respect to specs)***
ADC Samples	***12-bit, 64 MS/s***	***14-bit, 100 MS/s***
Daughterboard capacity	***2 TX, 2 RX***	***1 TX, 1 RX***
SRAM	***None***	***1 Megabyte***

The USRPs allows flexibility between daughterboard; you could possibly swap daughterboard to suit your desired parameters. This flexibility provides its RF frontend the choice to operate in the desired portion of the spectrum.

4.2.3. Dynamic Spectrum Access Test bed

The experiment for the spectrum sensing was conducted at the Centre for Telecommunication Access and Services (CeTAS), School of Electrical and Information Engineering, University of Witwatersrand Johannesburg laboratory. This is an equipped wired and wireless laboratory, with several types of radio devices that help facilitate various wireless experiments. Several USRP devices are available and can be used to perform experiments with regards to the physical layer.

The GNU radio/USRP platform at CeTAS was used to demonstrate Dynamic Spectrum Access (DSA) and also verify the performance of the technique used in real-time.

The methodology for the spectrum sensing technique was briefly discussed before introducing the experimental platform upon which this experiment was conducted. The various equipment used was extensively discussed in terms of their various mode of operation. The test-bed used in conducting the experiment was briefly described.

4.3. POWER DETECTOR IMPLEMENTATION USING GNU RADIO& USRP.

4.3.1. System Setup

First step taken was to install GNU Radio on a personal computer (PC) running Linux OS with hardware characteristics capable of processing output samples from the USRP2 in a real time environment. Then a direct connection via a fast gigabit Ethernet port from the host PC to the USRP2 was created. Once the hardware connections were complete, a further step was taken in order to make the host PC be able to communicate with the USRP2. These further steps includes installing the Universal Hardware Drivers (UHD), updating the UHD drivers installed and then assigning an IP address to the host PC and USRP2 device. The Universal Hardware Device (UHD) is a USRP2 driver which enables communication between the USRP2 and the host PC. Assigning IP addresses enables the host PC to be able to interact with the USRP2 via IP packets. Once the Ethernet connection is made, the UHD is updated, the IP addresses are assigned, then a verification message between the host PC and USRP2 indicating the system is properly connected is confirmed via the command line interface from the host PC and the output from the USRP2 query is shown in Figure 4.7.

$ Sudo uhd_find_devices

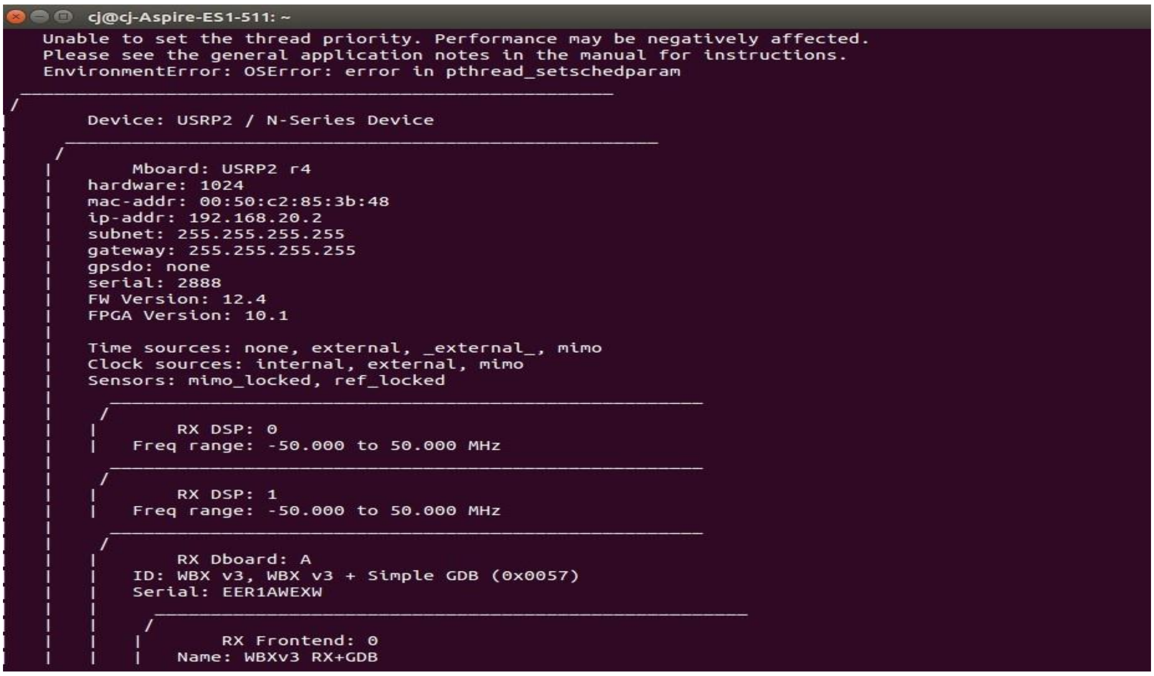

Figure 4.7. Brief output of the USRP2 query command.

Following the output from Figure 4.7, the MAC address, IP address, subnet mass, frequency range of the USRP2 board used and some other parameters where listed in the output display. This primarily denotes that the connection between the USRP2 and the host PC is intact. A GNU Radio application can now be executed via a Python routine or simply by using the GNU Radio Companion (GRC). A GRC is a graphical user interface to the GNU Radio top Python blocks. The experimental setup is shown in Figure 4.8.

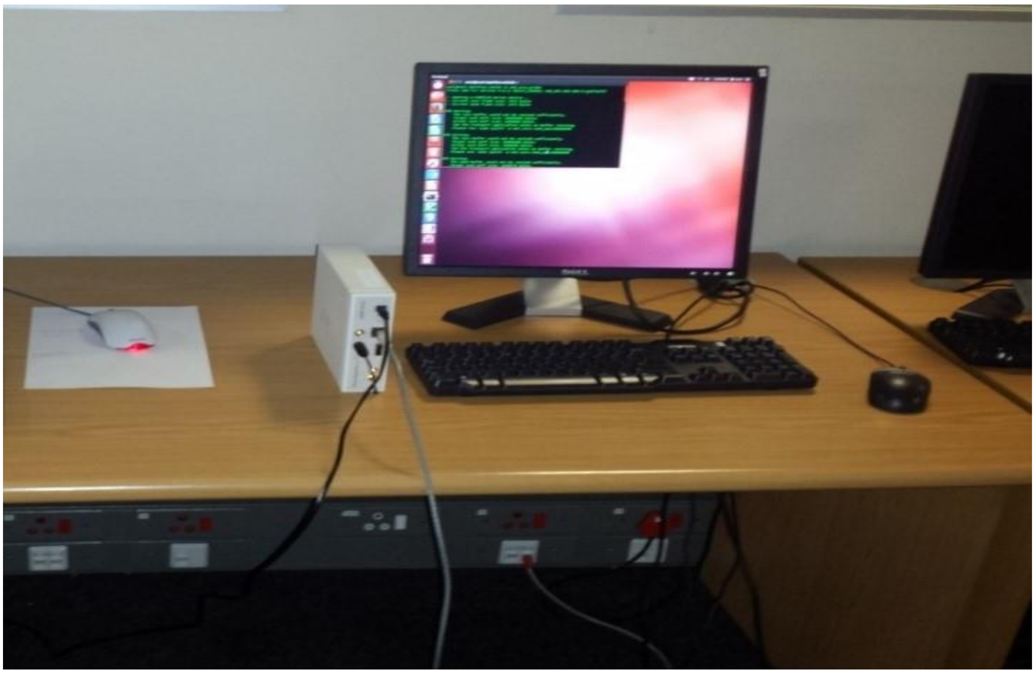

Figure 4.8. USRP2 and GNU Radio setup

In this research project, latest version of a wideband standard spectrum sensing routine available in the GNU Radio was deployed. This standard spectrum sensing routine functions more like a spectrum analyser and certainly flexible enough to monitor any radio frequency spectrum. However, there are commonly used spectrum analyser routines available in the GNU Radio library but these routines are not flexible enough. .i.e. hardly monitor more than 8MHz of bandwidth. The very commonly used spectrum analyser present in the GNU Radio library is the UHD_FFT.py routine. This routine primarily takes the Fourier Transform of the received signal in real time and displays it via the Graphical User Interface (GUI). The concern about this routine is that it is not efficient enough to detect spectrum holes and can only be performed at a very low decimation rate. The result of the UHD_FFT.py is shown in

Figure 4.9 showing the utilization of channel 22 of the TV broadcast frequency band in Johannesburg, University of Witwatersrand (WITS) Campus.

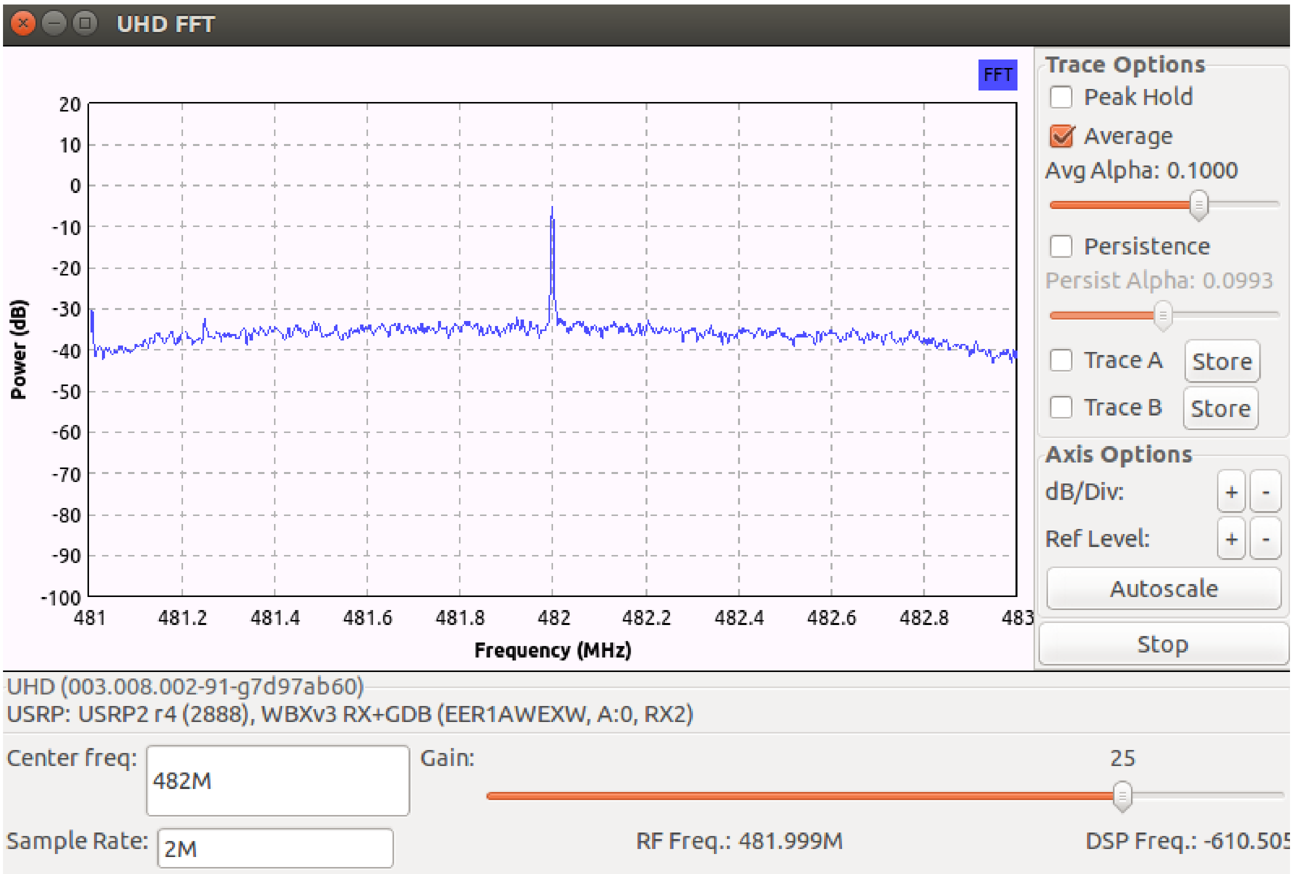

Figure 4.9. Output of UHD_FFT.py

Another routine that performs like a spectrum analyser in the GNU Radio library is the UHD_RX.py routine. This routine primarily receives signals from external source and forwards the received signals to the digital down converter (DDC) in I & Q formats. Afterwards, the received signal is then appended into a file format for easy interpretation. The only concern with this routine is that it only extracts data for a given centre frequency.

Hence, the modified wideband spectrum sensing routine in Appendix I implemented helps reduce the minor setbacks experienced in the standard routines.

4.3.2. Structural setup

The GNU radio is an open source software solution because of its compatibility with the Universal Software Radio Peripheral (USRP) [81]. This open source software was selected for the implementation of Dynamic Spectrum Access (DSA) using spectrum sensing technique. This open source software also combines a graphical programming language and in this case, it uses the python program, to provide a user friendly graphical user interface (GUI).

The structural flow chat diagram is shown in Figure 4.10, with certain characteristics features. These features are explained briefly below:

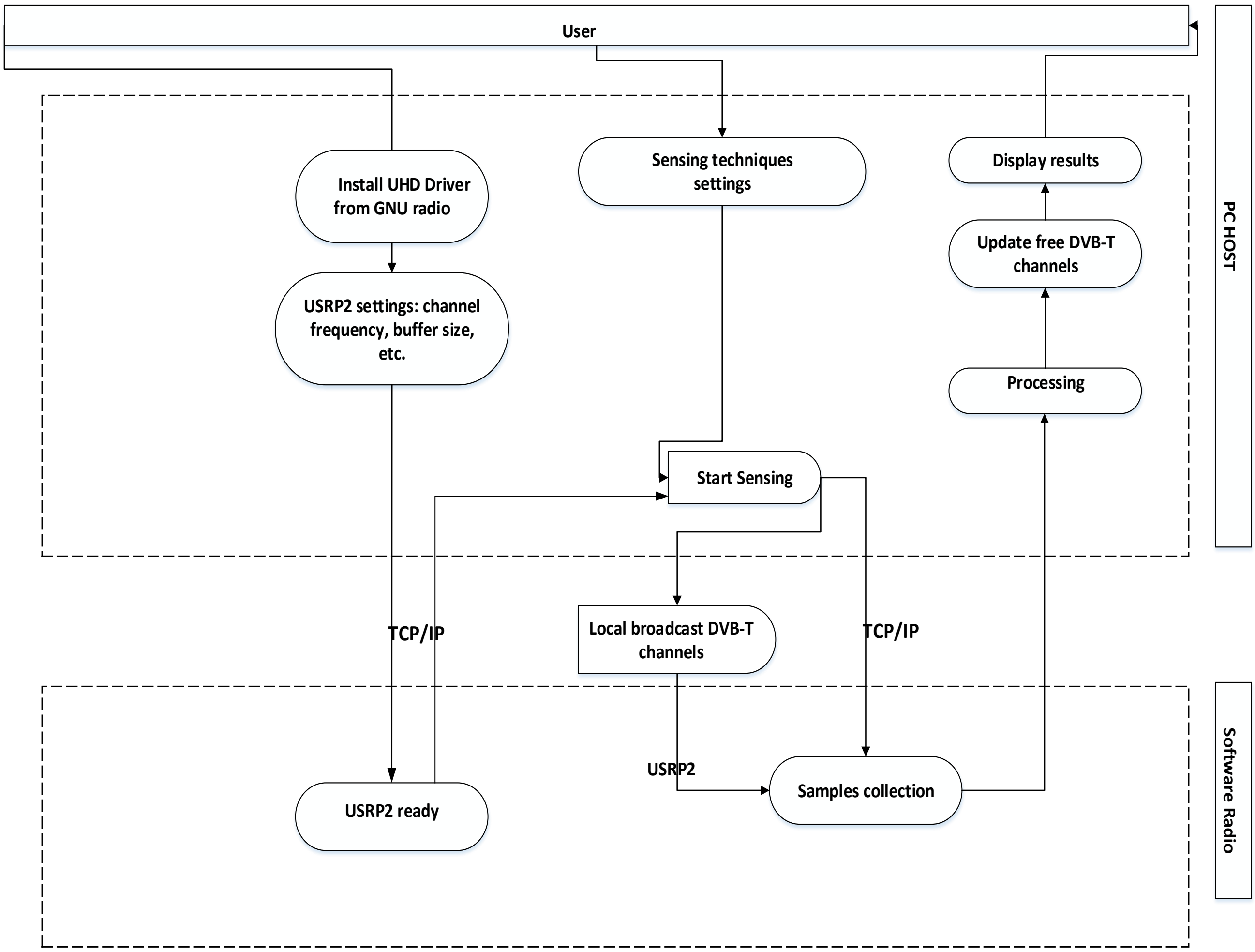

Figure 4.10 Structural diagram of the spectrum sensing tool.

The sequence starts off with installing the Universal Hardware Driver (UHD), this driver makes the USRP2 compatible with the GNU radio. Without this UHD installed properly, there cease to be any exchange of information between the USRP2 and GNU radio. Once that is done, the USRP2 settings are then configured to match the sensing requirements. After the settings have been configured, the USRP2 is now ready.

Since the spectrum sensing enabling technique or algorithm for the implementation has already been selected, the settings for the power detector is then configured to match the hypothesis stated previously. Once that is done from the host computer, the spectrum sensing of the broadcast radio frequency can commence.

Sensing the desired frequency to predict the location of the primary user and its spectral information i.e. bandwidth and carrier frequency should be the next step once the settings and parameters for sensing have been configured properly. The spectrum sensing technique comes as a default in most USRPs, but applying it in the real time implementation could be tricky. All that is needed is to edit the script to suit your outlined parameters. The wideband sensing script is available in Appendix I.

The sensing script is executed using a power spectral density based detector and this detector is operated using an adaptive threshold. This threshold is calculated based on the automatic estimation of the instantaneous noise floor. During the sensing period, the secondary user is not allowed transmission because it’s in the reception mode i.e. observing mode, and this period could also be referred to as the “quiet period”. The quiet period is that period when there is no secondary activity occurring on the RF spectrum. The opportunistic user tries to observe the activity of the primary user. It also can be described as the period when samples are collected, processed and decisions are made by the secondary user with regards to the primary user.

After the sensing of the radio or broadcast frequency spectrum is completed, the samples collected is processed and compared to the power detector hypothesis before a judgement is made. The judgement made is in form of available channels for opportunistic use and it’s been updated to the user.

4.3.3. GNU Radio Power Detector Methodology

A brief synopsis of what the implementation methodology entails are explained below:

Sensing Hypothesis

Complex baseband signals coming from the Field Programmable Gate Away (FPGA) in the USRP is practically used in the detection of incumbent signals. These complex base signals forces the cognitive device to draw conclusions based on two hypotheses [80]:

$$H_0 : Primary\ user\ absent$$

$$H_1 : Primary\ user\ present$$

Where H_0 and H_1 $satisfies\ all\ conditions\ in\ the\ equation.$

$$H_0 : X[n] = W[n] \; ; \qquad \textbf{(4.1)}$$

$$H_1 : X[n] = W[n] + S[n] \qquad \textbf{(4.2)}$$

Where n = 1, 2…, N; the number of samples N, h is the gain of the channel, the additive white Gaussian noise (AWGN) with zero mean is *W[n]*, *S[n]* is the primary user's signal and it is said to be a random Gaussian process with zero mean and variance of ∂_x^2[80]. For the purpose of this implementation, a signal source from the GNU radio companion would serve as secondary user while the USRP would act as a spectrum analyser.

Detector used/Sensing technique

Several detectors exists and can be used to sense primary signals or transmission e.g. the power or energy detector, cyclo-stationary detector and the matched filter detector etc. For the implementation of Dynamic Spectrum Access (DSA), the probability of missed detection P_{MD} must be at the least minimal level to ensure less interference issues on the incumbent user. Hence for the implementation of a Dynamic Spectrum Access (DSA), the power detector technique will be implemented. The power detector technique is the same as the energy detection technique where the decision rule will be based on the following [80]:

$$P\,(Y) \underset{H_0}{\overset{H_1}{\gtrless}} \lambda \qquad \textbf{(4.3)}$$

λ is the decision threshold and H_0 *and* H_1 are indications that a primary user is present or not. P(Y) is the received signal.

However, the reasons why the power detector is used in the implementation of DSA is because unlike other detectors, the power detector only relies on the signal power and its decision rule doesn't seem complex to implement compared to other feature detectors.

4.3.4. <u>GNU Radio Power Detector Implementation</u>

The structural representation in Figure 4.11 below depicts different signal processing block present in the detector, it also explains the processes encountered during the power detector algorithm implementation. The signal of the selected frequency is captured by the USRP2 and later forwarded as a tuning parameter. The raw data bit streams captured by the USRP2 is down converted into arrays of data by the WBX 2200 USRP2 front-end before its passed down to the USRP2 motherboard. The USRP2 daughterboard helps in the Analog to Digital conversion (ADC) of high frequency RF signal in air. The digital down converter (DDC) planted inside the Field Programmable Gate Away (FPGA) in the USRP2 helps marginalize the speed of the digitized signal received from the daughterboard. For the end user running GNU radio to be able to visualize the received signal, the marginalized digitized signal would have to be down converted again by the digital down converter (DDC) because at its current signal speed, the Ethernet port interfacing between the terminal and software define radio (SDR) cannot handle data inflow at such a high rate. The more reason it needs to be down converted once again.

In GNU radio, the received bit stream data from the USRP2 is converted into a vector format. The radio block responsible for this conversion is the *gr.stream_to_vector*. Then the converted data is passed into GNU radio FFT block. In this block, to get an effective result, samples experience windowing. Windowing primarily helps reduce spectral leakage effects. Samples are then channelled through the Blackman-Harris window to minimize the spectral leakage effect before the FFT.c2mag computes the squared magnitude of the FFT samples. After performing the squared magnitude of the FFT, decimation is performed in order to reduce the sample rate of the data to the preferred rate before it forwards it to the USRP2 as a tuning parameter. Lastly, the results after the fft_correction in dB is passed down to a sink block (*gr.message_sink*).

Python layer then collects and averages the N samples from the FFT. The samples received are in the form of FFT magnitude bins. The samples are then appended into a file format for easy analysis. The wideband spectrum sensing samples is available in Appendix II. The received samples are then plotted against selected frequencies. The changing characteristics of the frequency signals received is used to detect the white spaces present with respect to the previously stated hypothesis in the methodology.

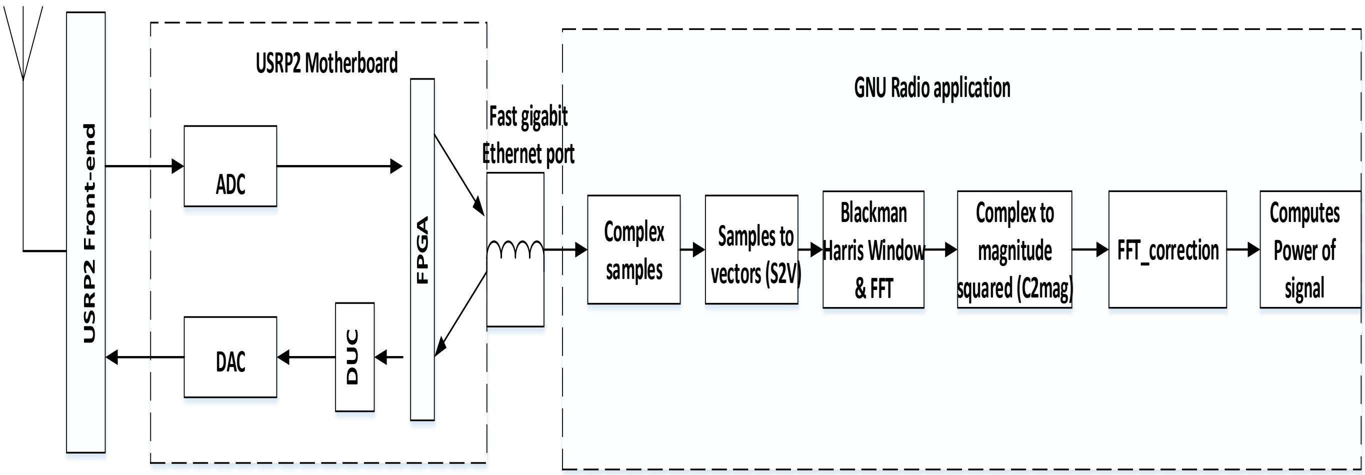

Figure 4.11 Flow graph of the power detector in GNU radio.

4.3.5. Experiment setbacks

This section discusses the problems or setbacks encountered while implementing the power detector algorithm on the broadcast frequency band. After a detailed structural analysis of the methodology was presented, in order to successfully implement the algorithm, there are several requirements which need to be fulfilled by the platform in use. However, the platform wasn’t efficient enough to meet these requirements. These requirements include:

- Hardware requirements/limitations: When the spectrum analyser command is being revoked via GNU Radio and the USRP2, the graphical user interface which comes on display depicts FFT magnitude values. Hence, in order to get the actual real values, calibration at various frequencies and sample rates needs to be implemented. The implemented calibration will vary from card-to-card because of the existing variability in analog gain signals. For a normalized voltage or power, calibration is necessary for a hardware setup.
  The spectrum sensing results were obtained using a decimation value of 12MS/s; more simplified results can be obtained at lesser decimation. A high gain antenna with tuner card can be used to enhance the receiver sensitivity.

- Enabling algorithm limitations: The energy detection or power detector enabling algorithm which was implemented had no understanding of the primary and secondary user signals, it also could not characterize the primary user signals from the secondary user signals. The analysis and results are based on the threshold level received from the environment. The Python routine implemented can sweep across large bandwidth but at a particular step. It cannot sweep across all bandwidth at the same time.

- Real-time analysis: The spectrum sensing routine failed to display results in real-time. This setback is as a result of the step wise wideband sensing and hardware limitations. Its inability to sweep across all bandwidth at the same time invariably implies that data are only obtained after the step wise sweep across all bandwidth is completed. This could result in loss of white space opportunities.

4.3.6. Problems encountered

The various problems encountered while implementing the wideband spectrum sensing is subject to the USRP2 firmware used. The USRP2 and GNU Radio is still a work in progress platform.

The hardware limitations with concerns regarding calibration, decimation rate, real-time analysis of results and enabling algorithm being implemented is subject to the equipment being used. A spectrum sensing equipment which comprises of a high speed processing unit being able to perform a computational demanding signal processing tasks with relative low delay are extremely expensive to procure. This setback was experienced while using the USRP2 in implementing the spectrum sensing methodology. The hardware limitation is subject to cost, this however influences the adoption of this methodology.

The power detector or energy detector implemented was based on the energy levels received. This enabling algorithm has a simplistic approach but not guaranteed in areas with low SNRs. In order to implement an efficient algorithm in areas with low SNR, it would incur more cost and at a high complexity rate. The more complex the algorithm, the more expensive it is to implement. This primarily influences the adoption of the spectrum sensing methodology.

The complexity of the methodology tells how easily adopted the technique would be. If it's less complex to implement, it would be more easily adopted but if the reverse is the case, its usefulness diminishes. The chances are quite high that a technique perceived to be easily implemented is more likely to be adopted.

Hence, a more developed firmware would solve most of the problems encountered while implementing the power detector algorithm on broadcast frequency band but at what cost is a major concern. This certainly is one of the major reasons as to why the methodology is not being adopted in major parts of the world.

4.4. RESULTS

Multi-dimensional spectrum sensing was performed on the broadcast frequency in South Africa and the results are extensively explained in this section. The experiment results were obtained from two different locations in South Africa. This is to enable geographical comparisons and to effectively observe spectrum utilization in various channels. The results described were effectively demonstrated during peak hours in order to ascertain the level of utilization of the frequency band. Figure 4.12 depicts the FFT magnitude of channel 21 of the broadcast frequency band at the University of Witwatersrand.

Figure 4.12 Spectrum analyser showing the FFT magnitude of channel 21.

The data received after implementing the USRP_spectrum_sense.py which is available on Appendix II was saved as a text file and loaded onto MATLAB for processing. The processing of this result was not done in real time due to hardware constraints. The channel usage of the broadcast frequency band on Wits campus and further away from the campus are shown in the results obtained. Two different types of plots were used to verify results deduced. These plots include spectral plots and frequency spectrogram plots.

Figure 4.13 shows the spectral plot of 474-488 MHz of the broadcast frequency band at University of Witwatersrand (WITS) campus. Due to hardware constraints, only the first two channels was sensed. Each channel with 8 MHz of bandwidth in size was sensed. The channel utilization can be seen with brief descriptions indicating the level of utilization. The heavy use indicates continuous activity occurring on that particular channel, the medium use indicates there is an activity but not continuous while the sparse use indicates no activity. The sparse use is said to be a white space. Based on Figure 4.13 it can be deduced that both channels were heavily utilized at the particular time the sensing measurements were taken.

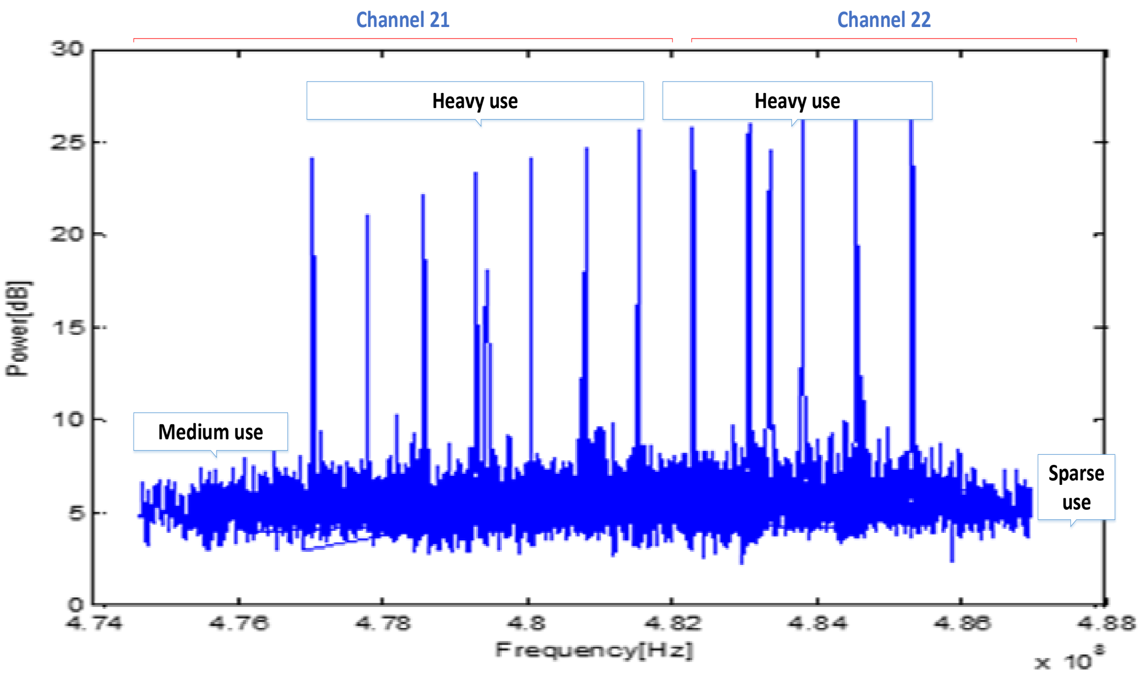

Figure 4.13 Spectral plot from 474-488MHz at WITS campus.

The channels on display in Figure 4.13 are channels sensed during noon hours of the day on campus. Hence, to be able to detect spectrum holes, a measurement was conducted again at a different site near another city area on the same day but at a different time interval. The reason for choosing a different location is to determine the level of activity occurring on each channel of the frequency band and to determine what time of the day the channel is frequently being used. The experiment was conducted at noon hours of the day. The initial location was WITS campus. The spectral plot obtained from the new location is shown in Figure 4.14.

The level of activity in each channel is shown. This activity indicates a progressive and geographical variation in the utilization of the broadcast frequency spectrum. The spectral plot of both geographical locations indicates that the spectrum occupancy is quite high and the channels are heavily utilized in both scenarios.

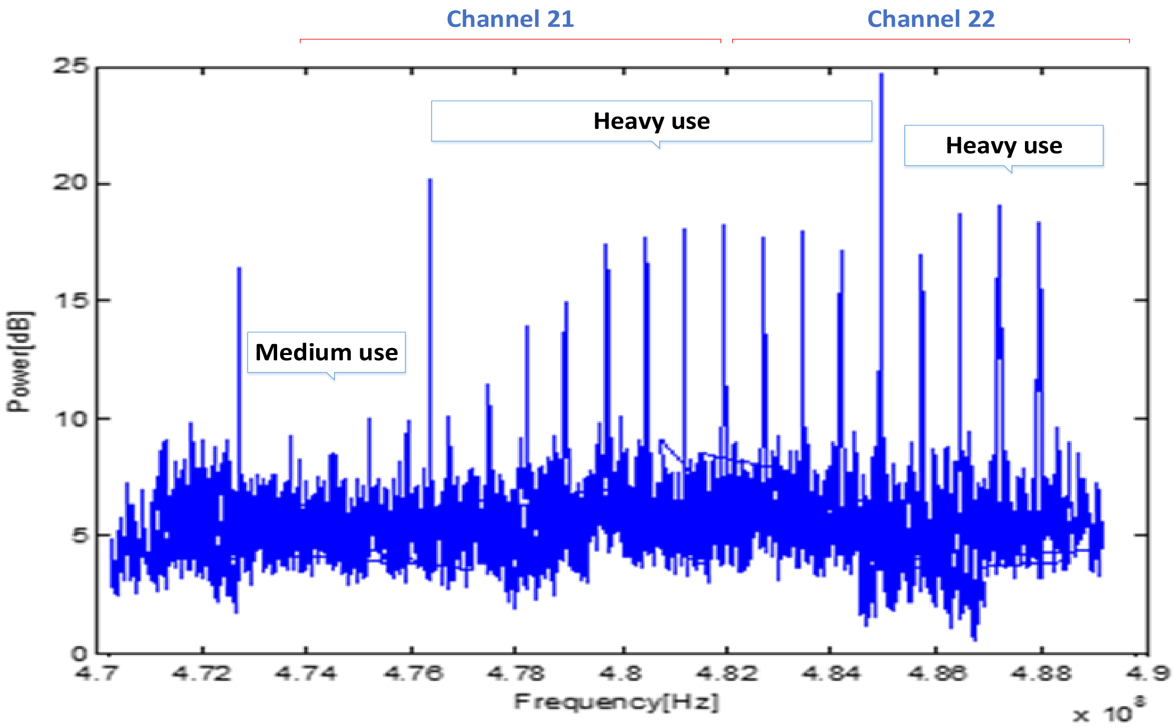

Figure 4.14 Spectral plot from 470-490 MHz at North-cliff.

The second plot which is the frequency spectrogram plot was used to verify result obtained. Frequency spectrogram plots are reliable enough to spot the threshold levels and to possibly come to a decision on which part of the spectrum is available for opportunistic use. The frequency spectrogram plot shown in Figure 4.15. A spectrogram is a time varying visual representation of a spectrum signal. The colour bar at the right side of the frequency spectrogram plot denotes the distinct levels of energy values. To be able to detect white spaces at a particular threshold, the axis colour with time and frequency are compared.

A spectrogram plot showing the different energy values with respect to frequency and time at the WITS campus is shown in Figure 4.15 below. The red portions in the frequency spectrogram plot in Figure 4.15 depict white spaces or ineffective use of the bandwidth at a particular time and frequency. Due to the frequency step used, the ability to differentiate one colour from another was possible but more clarity can be obtained with a wider frequency step.

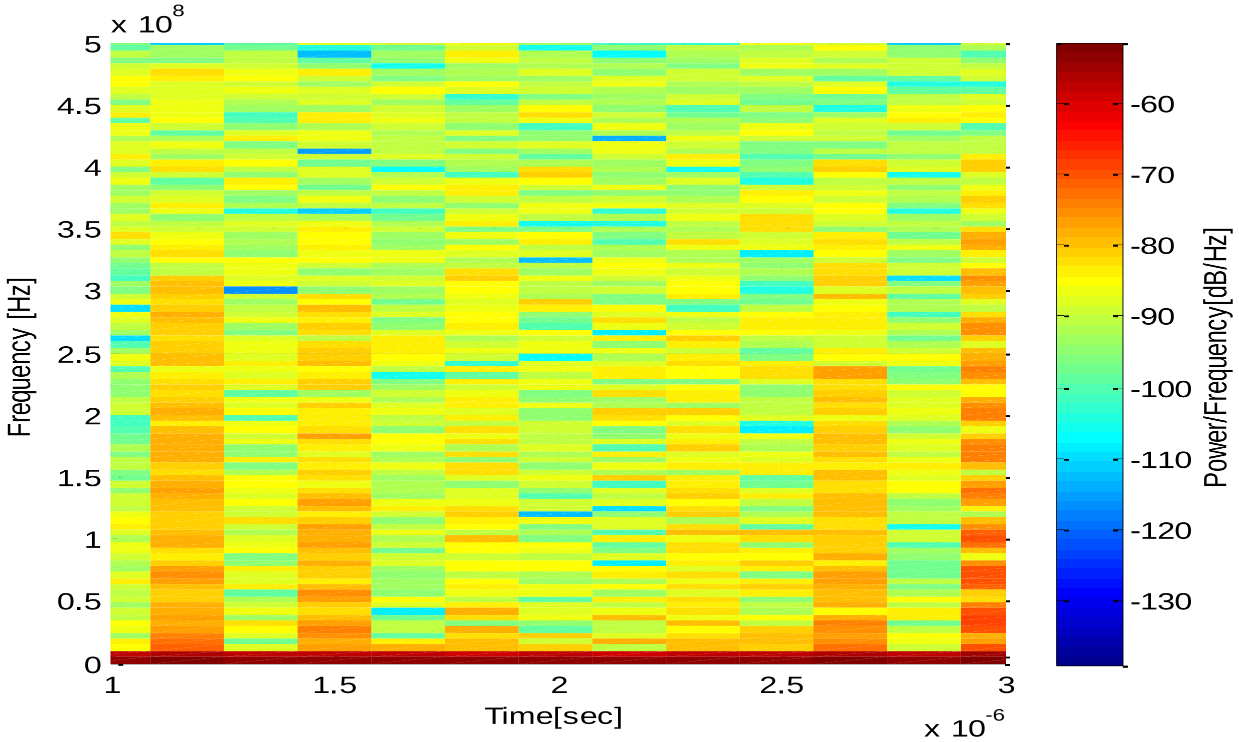

Figure 4.15 Spectrogram plot of the broadcast frequency at WITS campus

The spectrogram plot at WITS campus was compared to the spectrogram plot obtained 20km away from campus. The Figure 4.16 depicts the spectrogram plot measurement which was obtained from a different site near another city area on the same day but at a different time interval. The same colour mechanism which was applied to the WITS spectrogram is applied to the new spectrogram plot.

Comparing both spectrogram plots with respect to the colour mechanism being used, the red portions indicates underutilization of frequency band while the rest varying coloured portions represents different energy values of the frequency band.

The frequency spectrogram approach is more like the waterfall approach. It shows the activities on the spectrum band with respect to energy or gain levels. Based on the two spectrogram plots, it can be deduced that no spectrum hole was recorded at the particular time of sensing on the TV broadcast frequency band. However, shades of red portions were observed on some other frequency band at the time of sensing.

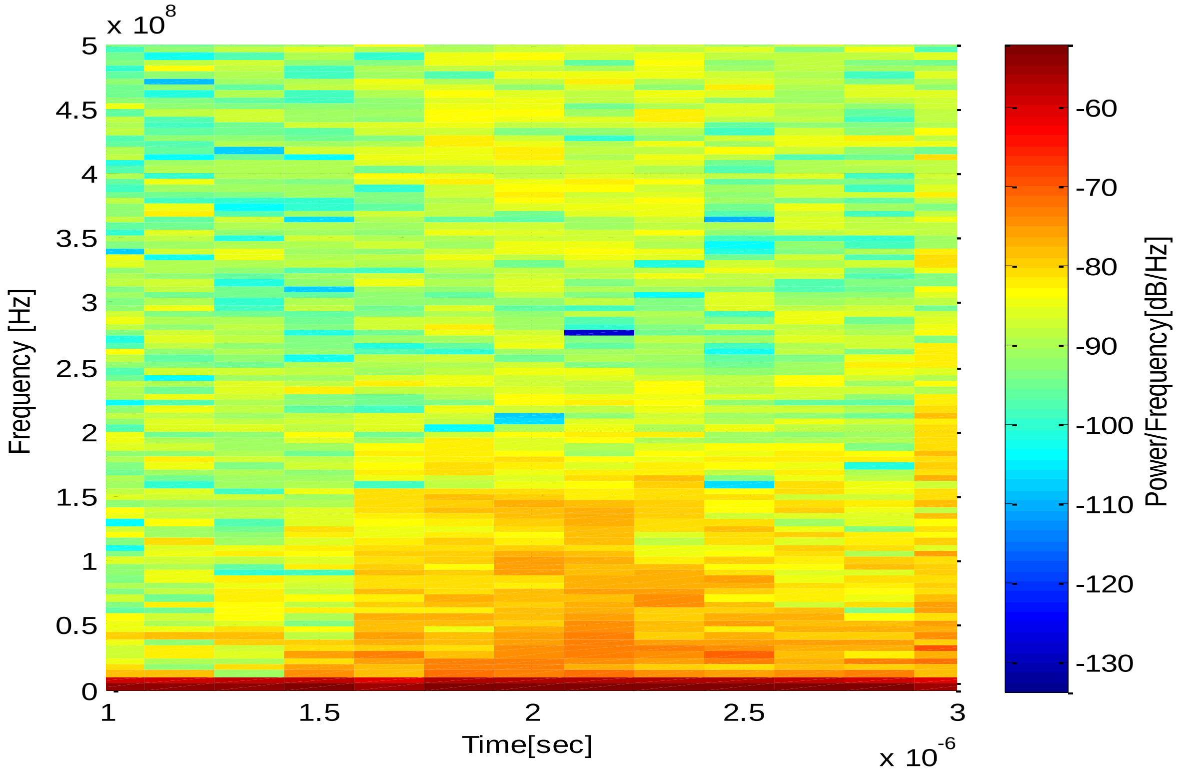

Figure 4.16 Spectrogram plot 20km away from WITS campus

The dynamic spectrum access implementation using GNU Radio and the USRP2 was described in this section. Certain plot which includes spectral plot and the spectrogram plot was presented and used to explain the results obtained via spectrum sensing. A multi-dimensional sensing was performed and the analysed result obtained was with respect to certain geographical location. However, the results indicate no availability of white spaces on the sensed TV broadcast channels at the time of sensing.

The spectrum sensing enabling algorithm implemented primarily operates on energy or threshold levels. It doesn't need prior information of the users on the band. The only problem with this technique is its ability to perform effectively in areas with low signal to noise ratio. This major concern and much more as discussed in the literature however, hinders the adoption of this methodology.

4.5. Geo-location Spectrum Database (GLSD) Implementation

Dynamic spectrum access technologies namely: spectrum sensing for cognitive radio and geo-location spectrum database are primarily the most adopted approaches for opportunistic access of the radio frequency spectrum globally. While the spectrum sensing approach has already been demonstrated and results been documented in this report, the geo-location spectrum database for dynamic spectrum access will also be demonstrated. Results and observations from the spectrum database demonstration would be compared to that of the spectrum sensing technique in order to ascertain the best approach or technique for spectrum management.

Unlike the spectrum sensing technique with several enabling algorithms, the geo-location spectrum database approach doesn't have enabling algorithms, it primarily is a repository which stores information with regards to a radio frequency spectrum and this information stored in the spectrum database can only be accessed by an end user via a web interface.

The spectrum database structure and composition depends on the regulatory policies governing its implementation. For example, in South Africa, the geo-location spectrum database is divided into regional databases with a master database coordinating all the activities of other regional databases. South Africa has got quite a large land mass, having one spectrum database to serve South Africa as a whole could be quite tasking on the side of the spectrum database, considering the fact that over 40million devices would be trying to access the spectrum database at a different time.

For the implementation of dynamic spectrum access using a geo-location spectrum database, the CSIR spectrum database in South Africa is used for this demonstration.

4.6 Geo-location Spectrum Database (GLSD) Methodology

This section describes the geo-location spectrum database methodology and how this methodology is applied or used to implement dynamic spectrum access in TV white spaces (TVWSs).

The structure of this research work commenced with a well-documented literature on the geo-location spectrum database, its operation, regulatory issues governing the adoption of the technique, certain trials conducted using the technique and results from the trials etc.

However, the basis of a well-documented literature on the geo-location spectrum database methodology is to instil a common familiarity with this methodology also while gaining more familiarity, narrow down the knowledge and understanding obtained from this methodology to focus more on the objectives of the research work.

Regarding the experimental approach, the experimental results were obtained from two different locations to enable effective comparison. A wideband sensing using the geo-location spectrum database was implemented on the TV broadcast frequency band. There were no hardware limitations as to the maximum amount of bandwidth that can be sensed. The results obtained were processed in real-time.

The geo-location spectrum database setup comprises of a PC running Ubuntu connected to the internet, static whitespace device nodes and an available regional spectrum database. The geo-location spectrum database provides a user friendly graphical user interface which aids in the interpretation of results obtained in real time.

The basic structural setup and composition of the geo-location spectrum database and how dynamic spectrum access or opportunistic spectrum access is implemented using the spectrum database in TV white spaces is discussed in details in the following sections.

4.7 CSIR Geo-location Spectrum Database (GLSD) Platform

4.7.1. Schematic structure of a spectrum database platform

To setup a spectrum database, several web programming languages and technologies are required. These programming languages are used to develop the structure of a spectrum database platform where information with regards to a radio frequency spectrum is being displayed. Figure 4.17 below depicts a typical architecture of a spectrum database and its operations. This spectrum database platform consists of a web server running MySQL, this is a programming language usually used to create a server which helps in managing the activities that occurs in the spectrum database, the Bing Maps server access assists by providing geographical location of an area or locality, and a computer with a browser connected to the internet.

Once the computer is active and online, the end-user locally enters the Universal Resource Locator (URL) of the web server address. The Bing Maps resources are then accessed and a digitized image in form of a map is then displayed on the screen of the end-user's computer. A little portion of the screen represents information of available TVWSs from the spectrum database computation.

The spectrum database consists of a data structure storing the following available information [29, 84]:

- Longitude and latitude coordinates: Each coordinates depicts the centre of a pixel area.
- The Criteria: this feature is made up of two options namely; the desired propagation model, and the desired height above average terrain (HAAT) of the white space devices (WSDs)
- EIRP levels: Maximum transmitting power of WSDs in watts or milli-watts, depending on the channel coordinates.
- Ultra-High Frequency channel number: Ranges from 21-68 channels

The spectrum database information is geographically centred in Pretoria, South Africa.

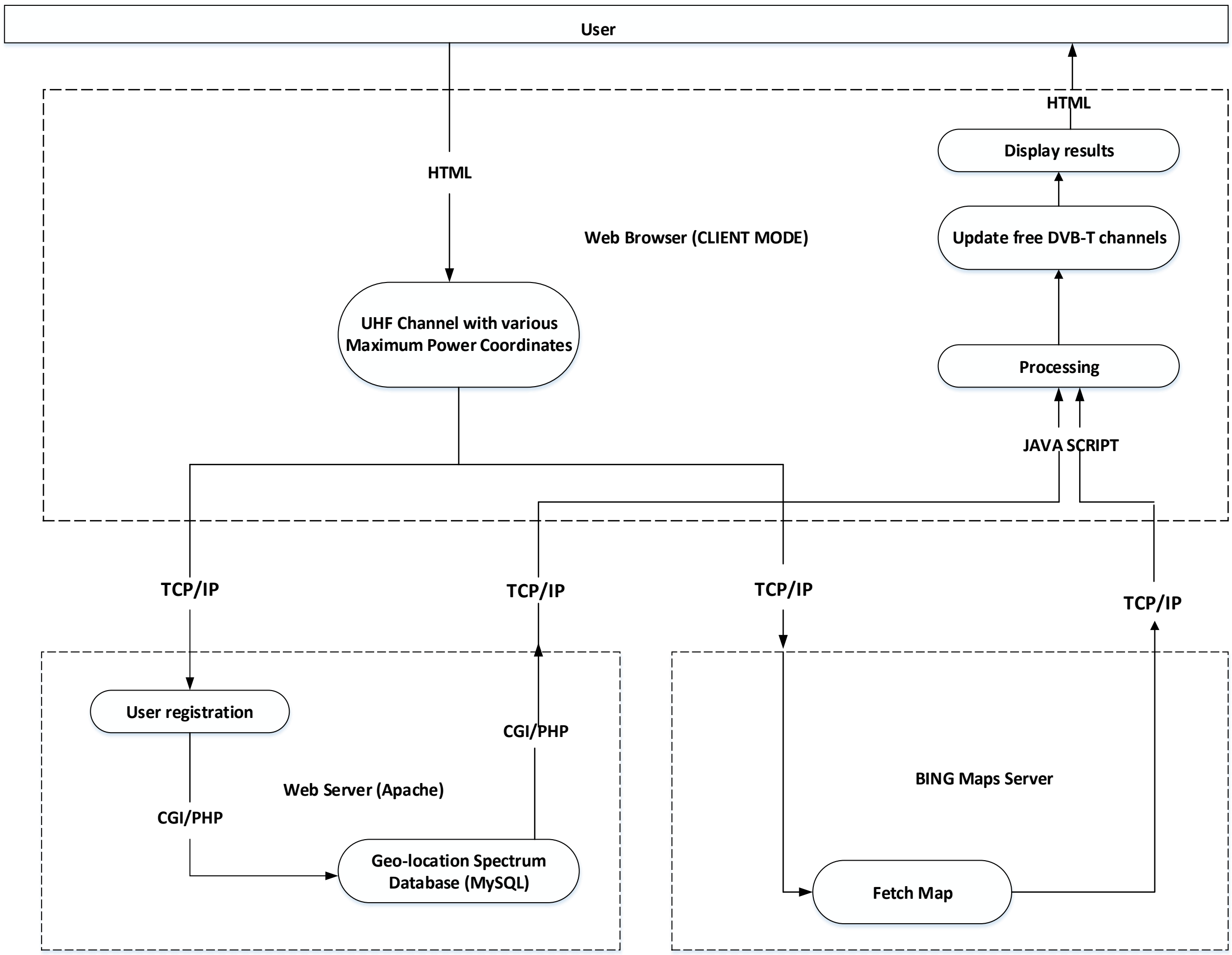

Figure 4.17 Structural composition of a spectrum database [75].

4.7.2. Graphical User Interface (GUI) of the Geo-location Spectrum Database

An interactive web page running HTML language is used to create a graphical user interface (GUI) for a spectrum database. The graphical user interface interprets the session orderly so that the end-user is able to view information on the availability of a channel being presented and possibly be able to configure the information presented to suit a particular requirement. This graphical user interface is shown in Figure 4.18. The white space map is characterized by specifying [29]:

- TV channels: UHF and VHF channels selection. This feature is characterised by two main parts; (1) the very high frequency (VHF) table which displays channels in little boxes starting from number 4 to number 13 (channel number 12 is excluded), (2) the Ultra High Frequency (UHF) table which displays channels in little boxes starting from number 21 to number 68. After performing the channel computation, the box(es) with green colour show available white space channels, while the white boxes mean that these channels are not available for TVWS network operations in that particular area.

- Maximum EIRP levels: Maximum power levels (between 40miliwatt and 4watts) used for channel transmission.
- The Map type: This feature is the largest space on the interface, the tick boxes on the top right hand side of the map permits different adjustable views. Adjustable different zoom levels exist by using the slider bar on the left hand side of the map. Additionally to adjust the different pan levels, click and drag to any desired point on the map.
- The info window: By default the info window is a rectangular box that pops up on the map showing a default location in latitude and longitude coordinates. However, the info window will request the marker be dragged to the desired location (this can be the location of a white space device) or it will request the desired location coordinates be typed in the form located at the right most side of the page. Either of the two methods will allow the database to do some calculations and output the following on the info window, the (1) amount of available free TVWS channels, (2) amount and size of the contiguous bandwidth.
- The signal strength power level legend; This is a colourful feature located at the top left most part of the map, it primarily gives hint on different TV station signal strength power levels found in their contours.
- TV stations signal strength contours: These features displays the signal strengths of each station of interest.
- The criteria: The feature is characterised by forms having two options namely; (1) selection of a desired propagation model, (2) selection of a desired height above average terrain (HAAT) of the white space device. Currently, the database supports white space devices with transmitting power (EIRP) ranging from 40 mW to 4 Watt. Ultimately, to search for available channels, click on the button written in short “search channels” (meaning search for available TVWS channels).

- The site details button: This feature is located right below the map, once pressed it will give detailed information of all TV stations where the free TVWS channels are found.

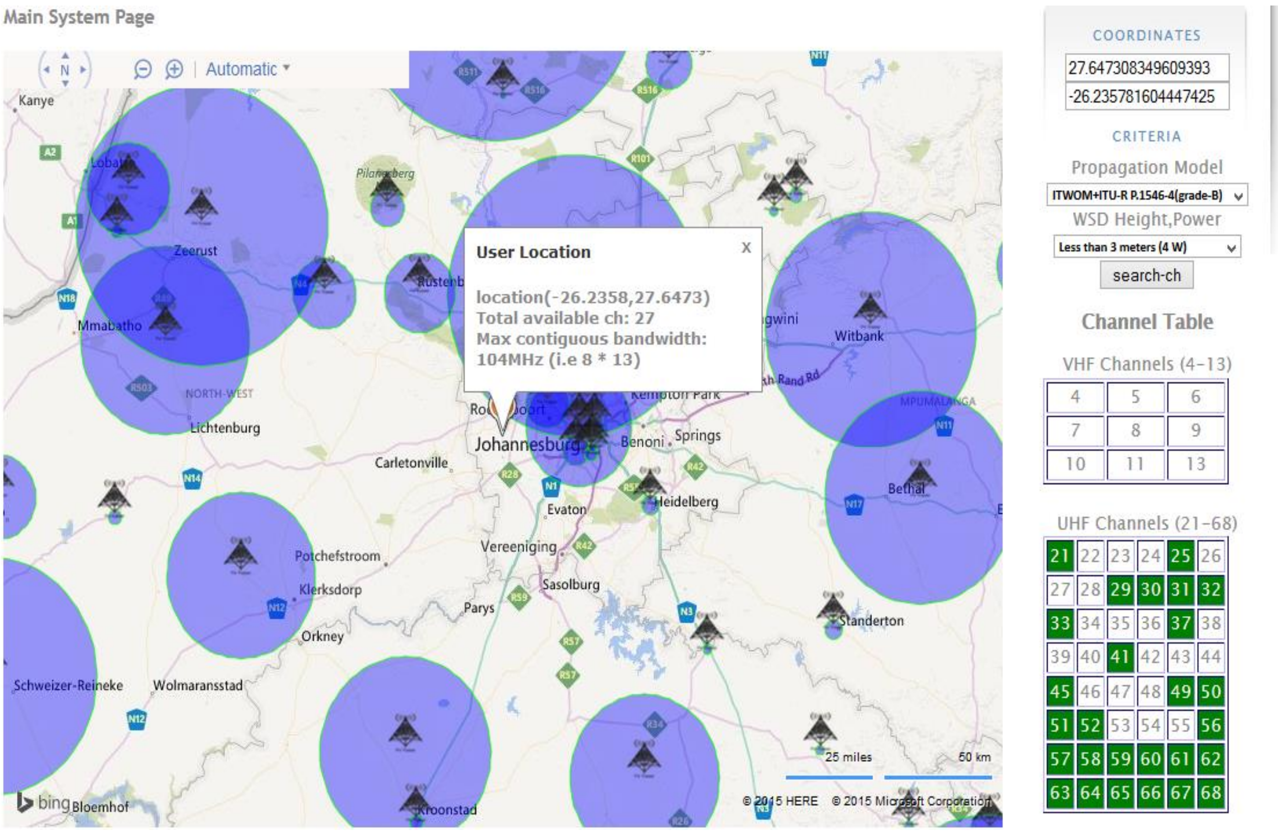

Figure 4.18 The GUI of CSIR Geo-location spectrum database [29].

4.8 Procedures on Dynamic Spectrum Access Implementation.

The several procedures taken to implement the Dynamic Spectrum Access (DSA) using geo-location spectrum database are listed below. These steps are primarily the communication that occurred between the end-user device, white space nodes and the spectrum database. In this case, a multi-dimensional sensing for available channels was conducted i.e. frequency, time and geographical place. Figure 4.19 depicts the pattern of communication between the device nodes and the regional spectrum database. The several procedures taken include:

- The white space device node used was accredited by the regulator, this accreditation comes with a unique identifier (ID) from the regulator, and in this case, ICASA does the accreditation in South Africa. On communicating with the regional spectrum database in Gauteng, the spectrum database synchronizes with the device node by requesting for this unique identifier (ID) before it registers the device on the database. Once that is presented, the white space device node is registered.

- The end-user device now tries to establish a connection to the white space device node via a signalling channel. The white space device node on getting the communication request from the end-user device, decrypts the information being sent, interprets the message and then forwards it to the Regional Spectrum Database covering the specific region. The communicated signalling information includes device registration, location of device and type of communication session.

- The Regional Spectrum Database on receiving the messages from the white space nodes, checks its pool of registration for authenticity then relates back to the white space node with information regarding the channel of interest and permitted transmit power of end-user devices.

- The white space device node upon receiving the parameters from Regional Spectrum Database, communicates back to the destination end-user device via the source end-user.

- The end-user device on receiving the information acknowledges by confirming it availability and location.

- Then the white space device node communicates to the end-user device with available channels for opportunistic use and their associated transmit power levels.

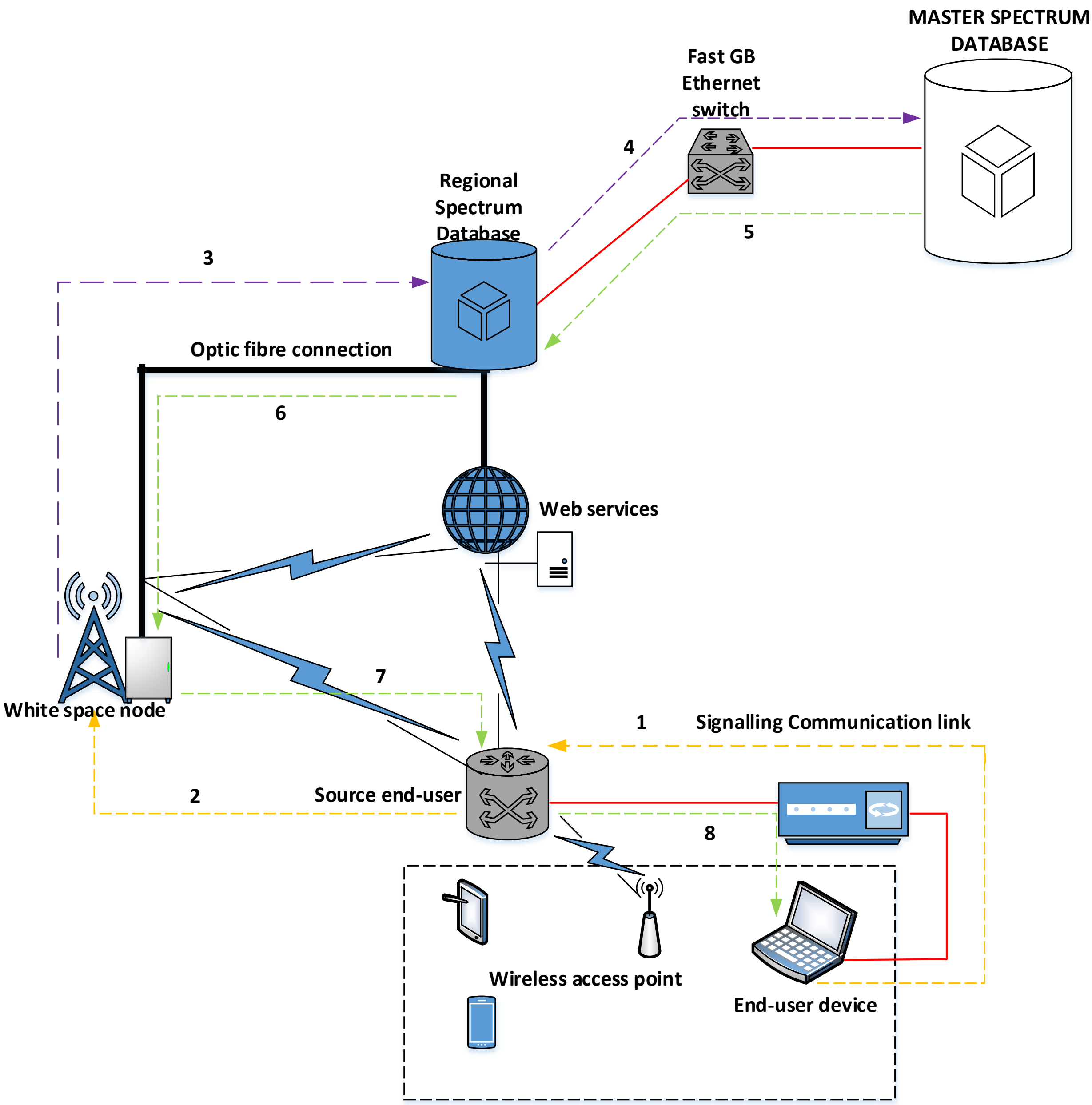

Figure 4.19 Dynamic Spectrum Access using Geo-location Spectrum Database technique

4.8.1. RESULTS

Dynamic spectrum Access (DSA) was been implemented using the geo-location spectrum database. Multi-dimensional sensing using the spectrum database indicates that at certain period of the day, certain time and geographic location there were certain channels available in the TV broadcast frequency for opportunistic use. The results from the demonstration shows the demonstration was centred at Johannesburg as indicated in Figure 4.20 during peak period. The result indicates Ultra-High Frequency (UHF) channels in green boxes shown in Figure 4.20 are available for opportunistic use. While the UHF channels in the white boxes indicates that these channels are not available for opportunistic use.

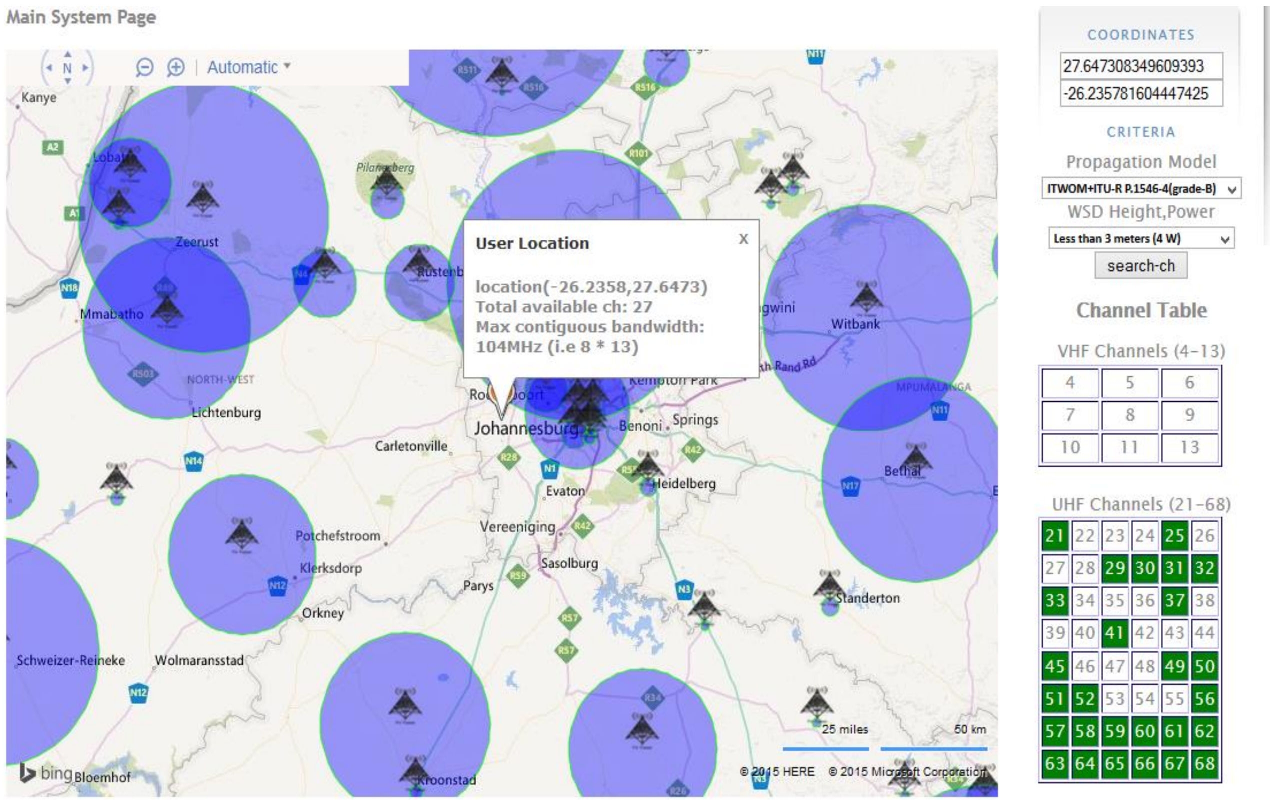

Figure 4.20. A Geo-location Spectrum Database (GLSD) in South Africa [29].

The activity on the spectrum is also shown in Figure 4.21. The channels allocated to licensed users are either being used or idle at a particular period of the time.

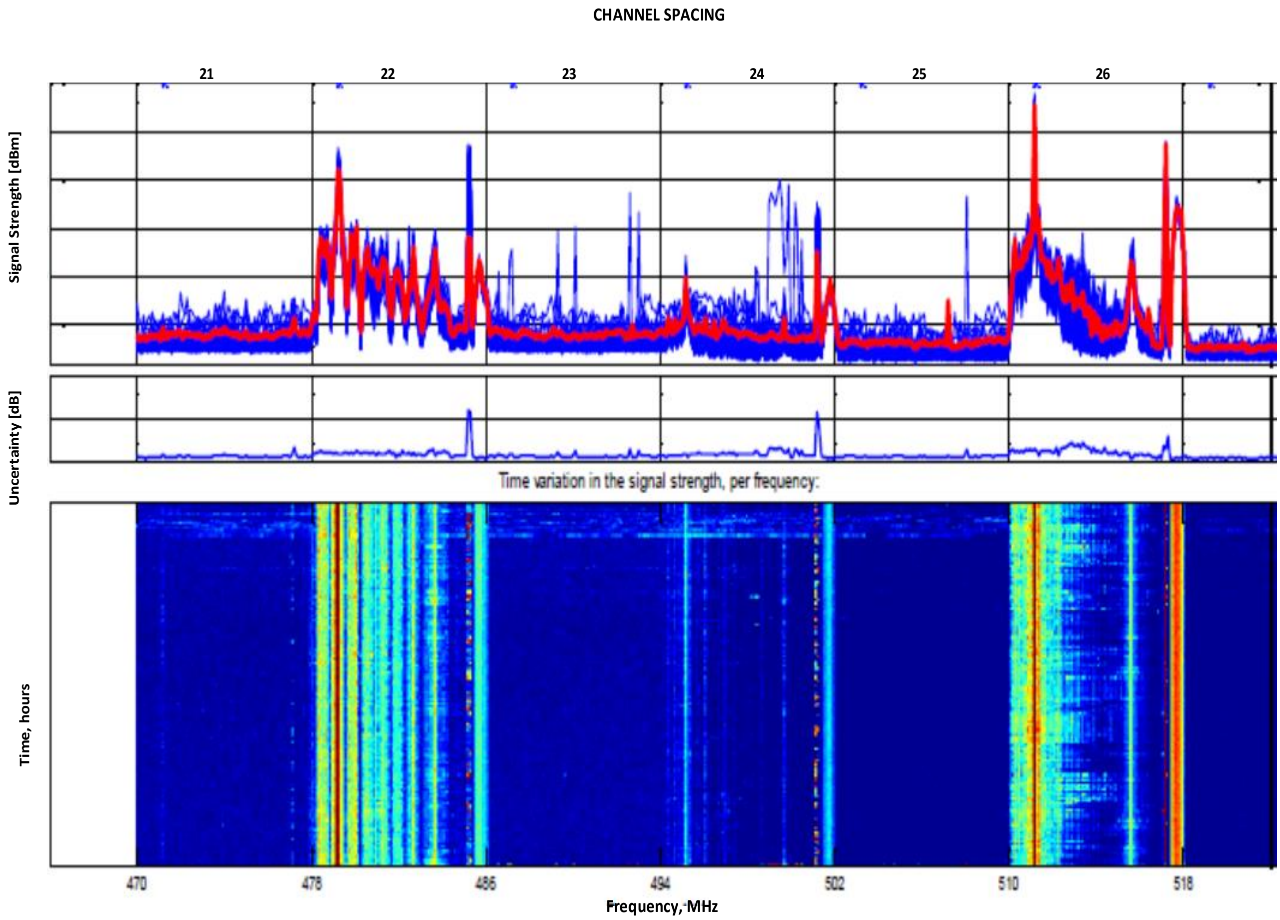

Figure 4.21. Activity on the spectrum using the Geo-location Spectrum Database [29]

The heat map or waterfall plot explains much better in terms of activities occurring on certain channels of the broadcast spectrum. The pale blue section indicates no activity and this means that channel is available for opportunistic use.

To further exploit the dynamism of the geo-location spectrum database which entails a user friendly interface, the area of search for TV whitespaces is narrowed down to the campus vicinity. The results are shown in Figure 4.22. This primarily explains how the search for white spaces was narrowed down to be within the University walls and nearest surroundings. The results obtained definitely varied from the previous results. However, white spaces were found.

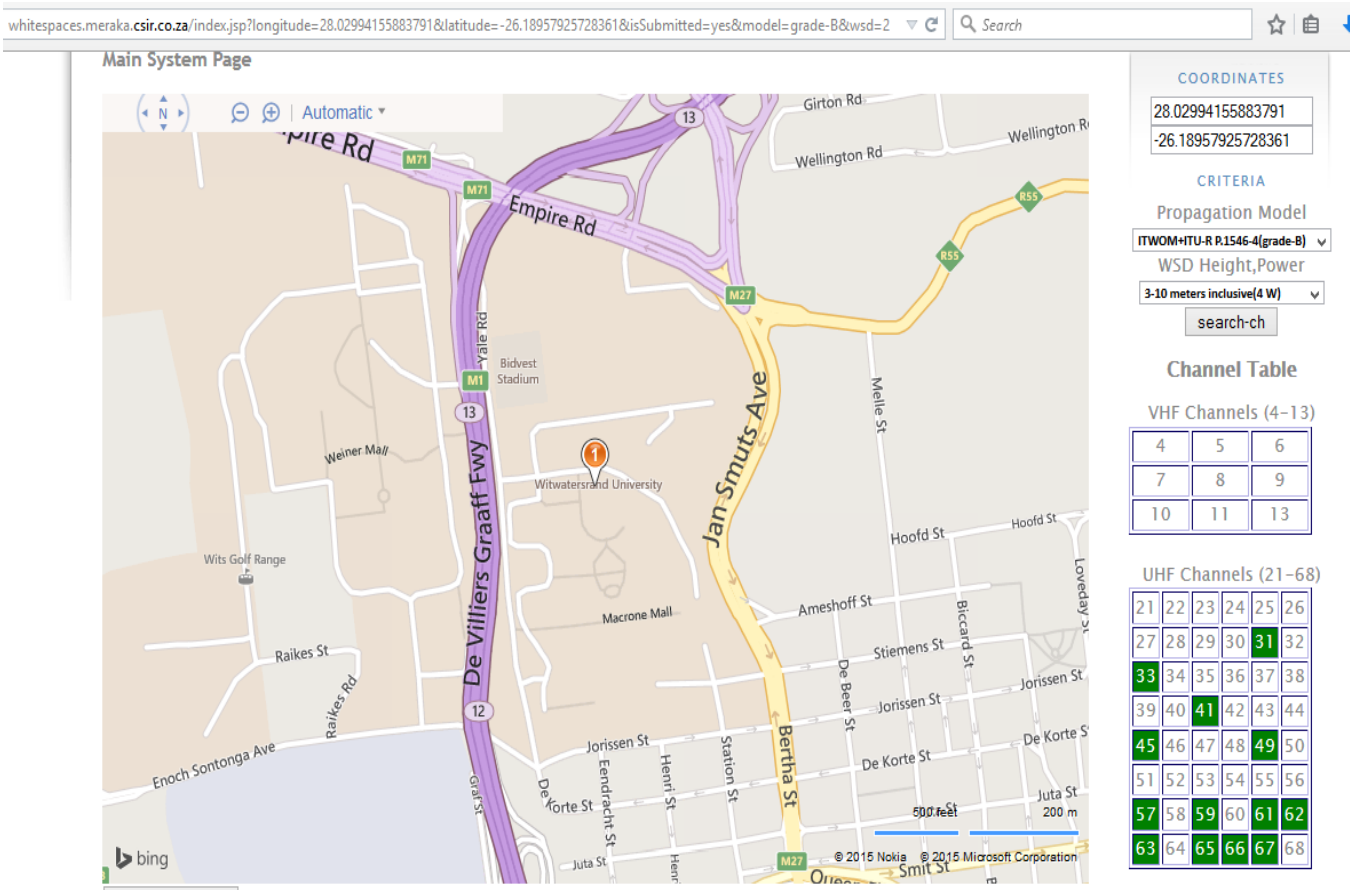

Figure 4.22. A Geo-location Spectrum Database (GLSD) in South Africa [29].

This user friendly interface feature is one of major observation recorded while implementing dynamic spectrum access with the geo-location spectrum database. The computational complexity and latency is quite minimal. The computational complexity includes processes that takes into account the proximity to licensed transmitters and receivers, specific transmitter types (e.g., full power digital TV, low power analog and digital TV), and specific receiver interference protection requirements (e.g., on the co-channel, adjacent channel, etc.) to avoid harmful interference.

Comparing both results obtained from the spectrum database, the white boxes indicate the channels are occupied while the green boxes indicate the channels are available for opportunistic use. The results obtained vary and indicates opportunistic spectrum access in TV white spaces.

4.8.2. SUMMARY

Dynamic Spectrum Access (DSA) was demonstrated using the most adopted Dynamic Spectrum Access technologies namely; spectrum sensing and geo-location spectrum database technique.

Based on the results obtained from the demonstration of both techniques/methodologies, several conclusions were deduced with respect to both methodologies and these conclusions were subject to how efficient the methodologies are in terms of performance, cost and practicality, and efficient utilization of the spectrum.

Furthermore, the results obtained from both methodologies were compared with respect to:

- Practicality: The energy detection algorithm implemented requires neither standardization nor any coordinated activity. Hence, this approach could likely be implemented quickly. However, considering reliability, the energy detection is certainly not known to be reliable in areas with low SNR. It also finds it difficult differentiating primary users (PUs) and secondary users (SUs). There are other enabling algorithm discussed in the literature but these algorithms have very high computational complexity which comes at a very high cost of implementing. This setback creates more concerns in the adoption of the sensing methodology.
  While geo-location spectrum database on the other hand does require coordinated activity to build, maintain and to specify its parameters to ensure appropriate availability.

Hence, in terms of rollout, the energy detector was easily implemented. While the spectrum database does require coordinated activity to build.

- Efficiency of spectrum utilization: The result obtained from the wide band spectrum sensing indicates the spectrum was effectively utilized at the time of sensing. However, this is because no false alarms were generated and it was able to detect signals. The geo-location spectrum database made more efficient and precise use of spectrum. Since the cognitive device is accurately updated on available spectrum, there is less worry for inefficient operation.

Hence, the geo-location spectrum database approach offers more from a spectrum utilization point of view; it also doesn't require any trade-offs between harmful interference and efficiency.

- Flexibility: While implementing Dynamic Spectrum Access using both methodologies, certain setbacks experienced such as hardware limitations and inability to obtain sensed results in real time while implementing the spectrum sensing methodology was never the case with the geo-location spectrum database. Based on the experienced gathered during the implementation, the geo-location spectrum database proves to be a more flexible approach when being compared to the spectrum sensing methodology. It also can accommodate the spectrum sensing technique.

Based on the above analysis, the geo-location spectrum database offers more in areas of spectrum utilization and performance but in terms of rollout it offers less because much standardization is required to set up a geo-location spectrum database. While the spectrum sensing approach is easily implemented (energy detection), it's not guaranteed to provide the required support in terms of proper detection of primary users because of its inability to perform efficiently in areas with low SNR [46]. This however results in the implementation of a more complex and reliable spectrum sensing technique which possibly requires efficient hardware for rollout and ultimately comes at a higher cost of implementation.

5.0 CONCLUSION AND FUTURE WORK

Dynamic Spectrum Access (DSA) using Geo-location Spectrum Database (GLSD) methodology and the spectrum sensing technique was implemented in this research report. The geo-location spectrum database is a new dynamic spectrum access technology in the world of spectrum management while the spectrum sensing technique has been in existence before the spectrum database; it faces implementation drawbacks due to its instability.

The aim of this research report is to recommend exploitation of available TV White spaces(TVWS) using both methodologies and to compare both methodologies based on the standards defined, in order to determine which methodology bests provides the required satisfaction during operation. Considering the main reason behind this comparison, which is to be able to develop a system or methodology with minimized interference level to incumbents?

In the implementation procedure, several comparisons were made with respect to factors such as flexibility, spectrum utilization, practicality and cost. Judging from the cost factor, the hardware requirements for the spectrum sensing technique is quite expensive and scarce (in terms of procurement) for various countries trying to adopt the technique. The geo-location spectrum database proved more efficient in terms of spectral utilization. The hidden node problem or misdetection problem is still a lingering problem in the spectrum sensing technique. However, cooperative sensing has been developed to help reduce the difficulties experienced in misdetection but it doesn’t completely eradicate the problem.

The spectrum sensing technique is still a technique under continuous research; it’s hardly being adopted in any part of the world. South Africa currently has decided not to adopt the spectrum sensing approach due to hardware scarcity, cost and its instability [76]. While the geo-location spectrum database on the other hand is certainly being adopted in various part of the world with flexible regulations being drafted on this methodology [31, 32, and 50] by various regulators. However, the geo-location spectrum database comes with a controlled setback. This means that, there are available and permanent solutions to the various setbacks experienced while implementing the technique.

Hence, based on the observations from this research project, recent papers published in the areas of cognitive radio and dynamic spectrum access, the geo-location spectrum database offers more protection and it’s quite an efficient approach to spectrum management.

However, for future purposes, the possibility of using a hybrid of the two approaches should be considered. A hybrid cognitive spectrum sensing and geo-location spectrum database framework is proposed to reduce the spatial-temporal spectrum hole in cognitive radio networks. However, this hybrid approach which combines the benefits of spectrum sensing and geo-location spectrum database appears feasible but a proper mathematical framework for effectively characterizing its advantages and disadvantages is yet to be explored. The goal of this hybrid approach is to maximize the utilization of spatial-temporal spectrum hole while satisfying the protection constraints for the primary users.

The issue of hardware cost and complex hardware capable of processing sensed results in real time should be considered. More smart receivers which offer high integrated low-cost hardware solutions for spectrum sensing in cognitive radio systems should be developed. These receivers should not be susceptible to radio frequency (RF) impairments such as in-phase and quadrature-phase imbalance etc.

The Technology Acceptance Model (TAM) should be incorporated in the evaluation process for both methodologies. Technology Acceptance Model (TAM) primarily explains user's behavioural pattern towards a new technology. It is used to evaluate user acceptance characteristics in information engineering systems. These user acceptance characteristics practically influence the developer's decisions towards the design and roll out of an information engineering system.

TAM structural composition is built on the basis of how users tend to behave when being presented with a new technology and how certain factors influence their decision about how to use this technology and when to use this technology. The two major factors on which the Technology Acceptance Model (TAM) is built are the Perceived Usefulness and Perceived Ease of Use (PEOU). Perceived Usefulness is defined as "the degree to which a person or individual believes that using a particular system would enhance his or her job performance" [85]. A system with a high rate of perceived usefulness is a system for which the users believe. This system is said to be the existence of a positive user-performance relationship [85].

While the Perceived Ease of Use is defined as "the degree to which a person believes that using a particular system would be free of effort" [85]. All things being equal, an application or system perceived to be easier to use is more likely to be accepted by users. Figure 5.1 depicts the structural composition of TAM and how each variable is dependent on the other.

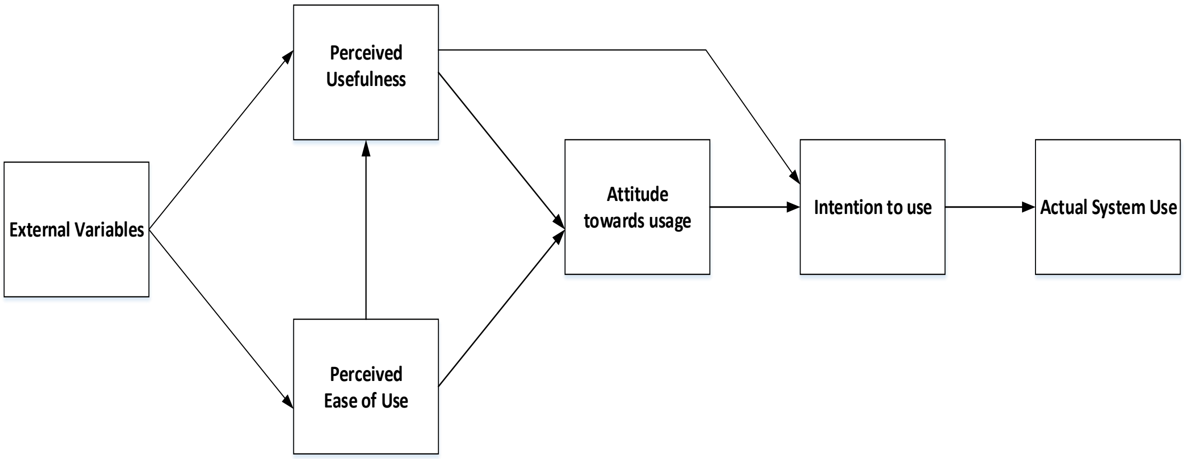

Figure 5.1 Technology Acceptance Model Structures [85].

Having explained in brief what TAM entails, this model once integrated into the methodology would assist in giving a clearer opinion on which Dynamic Spectrum Access (DSA) technology is largely accepted by the users.

Secondly, creating a spectrum sensing platform that obtains spectrum results in real time is an essential step towards the development of cognitive radio. The USRP2 and GNU radio falls short of this requirement. The USRP2 and GNU Radio platform is still a work in progress platform. However, an efficient platform for spectrum sensing would help reduce the delay experienced while performing spectrum sensing and provide sensed results in real time.

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APPENDIX I

The Python script responsible for the USRP spectrum sensing which is embedded in most recent versions of the USRP 2 terminal.

```
from gnuradio import gr, eng_notation
from gnuradio import blocks
from gnuradio import audio
from gnuradio import filter
from gnuradio import fft
from gnuradio import uhd
from gnuradio.eng_option import eng_option
from optparse import OptionParser
import sys
import math
import struct
import threading
from datetime import datetime

sys.stderr.write("Warning: this may have issues on some machines+Python version combinations to seg fault due to the callback in bin_statitics.\n\n")

class ThreadClass(threading.Thread):
    def run(self):
        return

class tune(gr.feval_dd):
    """
    This class allows C++ code to callback into python.
    """
    def __init__(self, tb):
        gr.feval_dd.__init__(self)
        self.tb = tb

    def eval(self, ignore):
        """
        This method is called from blocks.bin_statistics_f when it wants
        to change the center frequency.  This method tunes the front
        end to the new center frequency, and returns the new frequency
        as its result.
        """

        try:
            # We use this try block so that if something goes wrong
            # from here down, at least we'll have a prayer of knowing
            # what went wrong.  Without this, you get a very
            # mysterious:
            #
```

```
            #   terminate called after throwing an instance of
            #   'Swig::DirectorMethodException' Aborted
            #
            # message on stderr.  Not exactly helpful ;)

            new_freq = self.tb.set_next_freq()

            # wait until msgq is empty before continuing
            while(self.tb.msgq.full_p()):
                #print "msgq full, holding.."
                time.sleep(0.1)

            return new_freq

        except Exception, e:
            print "tune: Exception: ", e


class parse_msg(object):
    def __init__(self, msg):
        self.center_freq = msg.arg1()
        self.vlen = int(msg.arg2())
        assert(msg.length() == self.vlen * gr.sizeof_float)

        # FIXME consider using NumPy array
        t = msg.to_string()
        self.raw_data = t
        self.data = struct.unpack('%df' % (self.vlen,), t)


class my_top_block(gr.top_block):

    def __init__(self):
        gr.top_block.__init__(self)

        usage = "usage: %prog [options] min_freq max_freq"
        parser = OptionParser(option_class=eng_option, usage=usage)
        parser.add_option("-a", "--args", type="string", default="",
                          help="UHD device device address args [default=%default]")
        parser.add_option("", "--spec", type="string", default=None,
                              help="Subdevice of UHD device where appropriate")
        parser.add_option("-A", "--antenna", type="string", default=None,
                          help="select Rx Antenna where appropriate")
        parser.add_option("-s", "--samp-rate", type="eng_float", default=1e6,
                          help="set sample rate [default=%default]")
        parser.add_option("-g", "--gain", type="eng_float", default=None,
                          help="set gain in dB (default is midpoint)")
        parser.add_option("", "--tune-delay", type="eng_float",
                          default=0.25, metavar="SECS",
                          help="time to delay (in seconds) after changing frequency
```

```
[default=%default]")
        parser.add_option("", "--dwell-delay", type="eng_float",
                          default=0.25, metavar="SECS",
                          help="time to dwell (in seconds) at a given frequency [default=%default]")
        parser.add_option("-b", "--channel-bandwidth", type="eng_float",
                          default=6.25e3, metavar="Hz",
                          help="channel bandwidth of fft bins in Hz [default=%default]")
        parser.add_option("-l", "--lo-offset", type="eng_float",
                          default=0, metavar="Hz",
                          help="lo_offset in Hz [default=%default]")
        parser.add_option("-q", "--squelch-threshold", type="eng_float",
                          default=None, metavar="dB",
                          help="squelch threshold in dB [default=%default]")
        parser.add_option("-F", "--fft-size", type="int", default=None,
                          help="specify number of FFT bins [default=samp_rate/channel_bw]")
        parser.add_option("", "--real-time", action="store_true", default=False,
                          help="Attempt to enable real-time scheduling")

        (options, args) = parser.parse_args()
        if len(args) != 2:
            parser.print_help()
            sys.exit(1)

        self.channel_bandwidth = options.channel_bandwidth

        self.min_freq = eng_notation.str_to_num(args[0])
        self.max_freq = eng_notation.str_to_num(args[1])

        if self.min_freq > self.max_freq:
            # swap them
            self.min_freq, self.max_freq = self.max_freq, self.min_freq

        if not options.real_time:
            realtime = False
        else:
            # Attempt to enable realtime scheduling
            r = gr.enable_realtime_scheduling()
            if r == gr.RT_OK:
                realtime = True
            else:
                realtime = False
                print "Note: failed to enable realtime scheduling"

        # build graph
        self.u = uhd.usrp_source(device_addr=options.args,
                                 stream_args=uhd.stream_args('fc32'))

        # Set the subdevice spec
        if(options.spec):
            self.u.set_subdev_spec(options.spec, 0)
```

```
    # Set the antenna
    if(options.antenna):
        self.u.set_antenna(options.antenna, 0)

    self.u.set_samp_rate(options.samp_rate)
    self.usrp_rate = usrp_rate = self.u.get_samp_rate()

    self.lo_offset = options.lo_offset

    if options.fft_size is None:
        self.fft_size = int(self.usrp_rate/self.channel_bandwidth)
    else:
        self.fft_size = options.fft_size

    self.squelch_threshold = options.squelch_threshold

    s2v = blocks.stream_to_vector(gr.sizeof_gr_complex, self.fft_size)

    mywindow = filter.window.blackmanharris(self.fft_size)
    ffter = fft.fft_vcc(self.fft_size, True, mywindow, True)
    power = 0
    for tap in mywindow:
        power += tap*tap

    c2mag = blocks.complex_to_mag_squared(self.fft_size)

    # FIXME the log10 primitive is dog slow
    #log = blocks.nlog10_ff(10, self.fft_size,
    #                       -20*math.log10(self.fft_size)-10*math.log10(power/self.fft_size))

    # Set the freq_step to 75% of the actual data throughput.
    # This allows us to discard the bins on both ends of the spectrum.

    self.freq_step = self.nearest_freq((0.75 * self.usrp_rate), self.channel_bandwidth)
    self.min_center_freq = self.min_freq + (self.freq_step/2)
    nsteps = math.ceil((self.max_freq - self.min_freq) / self.freq_step)
    self.max_center_freq = self.min_center_freq + (nsteps * self.freq_step)

    self.next_freq = self.min_center_freq

    tune_delay  = max(0, int(round(options.tune_delay * usrp_rate / self.fft_size)))  # in
fft_frames
    dwell_delay = max(1, int(round(options.dwell_delay * usrp_rate / self.fft_size))) # in
fft_frames

    self.msgq = gr.msg_queue(1)
    self._tune_callback = tune(self)        # hang on to this to keep it from being GC'd
    stats = blocks.bin_statistics_f(self.fft_size, self.msgq,
                                    self._tune_callback, tune_delay,
```

```
                                dwell_delay)

        # FIXME leave out the log10 until we speed it up
            #self.connect(self.u, s2v, fftter, c2mag, log, stats)
            self.connect(self.u, s2v, fftter, c2mag, stats)

        if options.gain is None:
            # if no gain was specified, use the mid-point in dB
            g = self.u.get_gain_range()
            options.gain = float(g.start()+g.stop())/2.0

        self.set_gain(options.gain)
        print "gain =", options.gain

    def set_next_freq(self):
        target_freq = self.next_freq
        self.next_freq = self.next_freq + self.freq_step
        if self.next_freq >= self.max_center_freq:
            self.next_freq = self.min_center_freq

        if not self.set_freq(target_freq):
            print "Failed to set frequency to", target_freq
            sys.exit(1)

        return target_freq


    def set_freq(self, target_freq):
        """
        Set the center frequency we're interested in.

        Args:
            target_freq: frequency in Hz
        @rypte: bool
        """

        r = self.u.set_center_freq(uhd.tune_request(target_freq, rf_freq=(target_freq + self.lo_offset),rf_freq_policy=uhd.tune_request.POLICY_MANUAL))
        if r:
            return True

        return False

    def set_gain(self, gain):
        self.u.set_gain(gain)

    def nearest_freq(self, freq, channel_bandwidth):
        freq = round(freq / channel_bandwidth, 0) * channel_bandwidth
        return freq
```

```
def main_loop(tb):

    def bin_freq(i_bin, center_freq):
        #hz_per_bin = tb.usrp_rate / tb.fft_size
        freq = center_freq - (tb.usrp_rate / 2) + (tb.channel_bandwidth * i_bin)
        #print "freq original:",freq
        #freq = nearest_freq(freq, tb.channel_bandwidth)
        #print "freq rounded:",freq
        return freq

    bin_start = int(tb.fft_size * ((1 - 0.75) / 2))
    bin_stop = int(tb.fft_size - bin_start)

    while 1:

        # Get the next message sent from the C++ code (blocking call).
        # It contains the center frequency and the mag squared of the fft
        m = parse_msg(tb.msgq.delete_head())

        # m.center_freq is the center frequency at the time of capture
        # m.data are the mag_squared of the fft output
        # m.raw_data is a string that contains the binary floats.
        # You could write this as binary to a file.

        for i_bin in range(bin_start, bin_stop):

            center_freq = m.center_freq
            freq = bin_freq(i_bin, center_freq)
            #noise_floor_db = -174 + 10*math.log10(tb.channel_bandwidth)
            noise_floor_db = 10*math.log10(min(m.data)/tb.usrp_rate)
            power_db = 10*math.log10(m.data[i_bin]/tb.usrp_rate) - noise_floor_db

            if (power_db > tb.squelch_threshold) and (freq >= tb.min_freq) and (freq <=
tb.max_freq):
                print datetime.now(), "center_freq", center_freq, "freq", freq, "power_db",
power_db, "noise_floor_db", noise_floor_db

if __name__ == '__main__':
    t = ThreadClass()
    t.start()

    tb = my_top_block()
    try:
        tb.start()
        main_loop(tb)

    except KeyboardInterrupt:
pass
```

APPENDIX II

The wideband sensed results from the USRP2.

Centre Frequency	Frequency	Power	Noise floor
474375000	474675000	4,67941456	-96,077444
474375000	474681250	5,26423085	-96,077444
474375000	474687500	4,72356075	-96,077444
474375000	474693750	5,45005949	-96,077444
474375000	474700000	6,60986346	-96,077444
474375000	474706250	5,32226581	-96,077444
474375000	474712500	4,73037198	-96,077444
474375000	474718750	5,46436167	-96,077444
474375000	474725000	4,31079359	-96,077444
474375000	474731250	4,70777523	-96,077444
474375000	474731250	4,02227647	-96,077444
474375000	474743750	3,18618552	-96,077444
474375000	474750000	3,27629913	-96,077444
474375000	474756250	4,45562435	-96,077444
474375000	474762500	6,14404333	-96,077444
474375000	474768750	4,54234032	-96,077444
474375000	474775000	4,79060144	-96,077444
474375000	474781250	4,81284175	-96,077444
474375000	474787500	4,14536687	-96,077444
474375000	474793750	5,37131238	-96,077444
474375000	474800000	4,45452286	-96,077444
474375000	474806250	5,00070264	-96,077444
474375000	474812500	4,53274895	-96,077444
474375000	474818750	5,35396169	-96,077444
474375000	474825000	4,86532428	-96,077444
474375000	474831250	5,04018156	-96,077444
474375000	474837500	4,56132572	-96,077444
474375000	474843750	4,54532963	-96,077444
474375000	474850000	6,33146858	-96,077444
474375000	474856250	6,21814306	-96,077444
474375000	474862500	4,80723187	-96,077444
474375000	474868750	4,44050314	-96,077444
474375000	474875000	5,82121049	-96,077444
474375000	474881250	5,35326965	-96,077444
474375000	474887500	6,15045841	-96,077444
474375000	474893750	5,65900945	-96,077444
474375000	474900000	5,24237492	-96,077444
474375000	474906250	6,81633748	-96,077444
474375000	474912500	6,12707445	-96,077444
474375000	474918750	5,98829098	-96,077444
474375000	474925000	5,76687472	-96,077444
474375000	474931250	5,77686538	-96,077444
474375000	474937500	5,23276978	-96,077444
474375000	474943750	4,59832389	-96,077444

474375000 474375000 474375000	474950000 474956250 474962500	5,70512252 4,93658152 5,18266995	-96,077444 -96,077444 -96,077444